Fabrication and Characterization of Micro and Nano Scale SiC UV Photodetectors

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Abstract

The focus of this master thesis work is on the fabrication of micro- and nano-scale metal-semiconductor-metal silicon carbide (SiC) UV photodetectors and subsequent electrical and optical evaluation of the fabricated devices. The UV photodetectors have significant potential to address the needs of many applications such as detection of corona discharge and flames, industrial machine viewing, and bacteria in water or paper mills. Micro-scale devices in 4H-SiC and 6H-SiC have been fabricated successfully with good photoresponse and low dark current. Reduction in size of the 4H-SiC UV detectors from micro-scale to nano-scale has been achieved by the use of nano imprint lithography (NIL). The performance of these nano-devices have been characterized, and experiment results reveal good photo sensitivity at very low applied biases.
Acknowledgments

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<td>atomic force microscope</td>
</tr>
<tr>
<td>ARC</td>
<td>anti reflective coating</td>
</tr>
<tr>
<td>ASL</td>
<td>anti sticking layer</td>
</tr>
<tr>
<td>C-V</td>
<td>capacitance/voltage</td>
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<tr>
<td>CVD</td>
<td>chemical vapor deposition</td>
</tr>
<tr>
<td>DI-water</td>
<td>deionized water</td>
</tr>
<tr>
<td>IR</td>
<td>infra red</td>
</tr>
<tr>
<td>I-V</td>
<td>current/voltage</td>
</tr>
<tr>
<td>LPCVD</td>
<td>low pressure chemical vapor deposition</td>
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<td>MSM</td>
<td>metal semiconductor metal</td>
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<tr>
<td>NIL</td>
<td>nano imprint lithography</td>
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<tr>
<td>QD</td>
<td>quantum dots</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
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<tr>
<td>UV-LED</td>
<td>ultraviolet light emitting diode</td>
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</table>
Chapter 1

Introduction

In this chapter background and content of this master thesis project will be described along with some thoughts about applications for UV detectors.

1.1 Project description

This master thesis work has been carried out at Acreo, Kista, during October 2010 until May 2011. Acreo is a research institute which has been active in the SiC field since 1993 and covers all aspects of SiC technology from device design to epitaxy and device manufacturing. Acreo has also been developing the NIL technique since 2005. This has provided a good base for the fabrication of nano scale devices. For example, nano scale UV detectors based on GaN have been demonstrated \[1\]. The main goal of this project has been to fabricate silicon carbide (SiC) based metal-semiconductor-metal ultraviolet (UV) photodetectors by nano imprint lithography (NIL). Subsequent electrical and optical measurements of the fabricated devices should be done to characterize the product. Nano-scale MSM UV photodetectors on SiC has not been fabricated before. The NIL fabrication technique will bring the detectors from micro scale to nano scale, where higher sensitivity and faster time response can be expected \[2\]. In the long-term, it is believed that the effect of shrinking SiC device sizes to nano scale will have a dramatic effect on the performance of devices and open new avenues for the design of next generation SiC components and compact systems. UV detectors have significant potential to address the needs of many applications such as detection of corona discharge and flames, industrial machine viewing, and bacteria in water or paper mills. This can be achieved through the use of nanotechnology, which is an important enabling technology for the production of a complete detection system with high sensitivity and stability.

My work has involved the following tasks:

- Design of the SiC epitaxial structure and growth, together with experienced personnel at Acreo
- Clean room processing of the nano scale SiC UV detectors using NIL, reactive ion etching and metallization techniques
- Measurement of electrical and optical performance of the fabricated devices
- Written report
1.2 Extended Work

Originally the plan was five months for this project, but due to extension of the work also the
time plan was extended. In order to compare the nano scale to micro scale devices, it was
decided that micro scale MSM photo detectors should also be fabricated and characterized.
The fabrication of these detectors was done by ordinary UV photo lithography, metallization
and lift off processes.

Another extended work carried out was further development of NIL process based on exist
NIL technique developed at Acreo since 2005. New NIL resist, adhesion promoters, wafer-scale
NIL resist coating techniques and stamp replications were investigated to optimize stability
and high throughput of the NIL process. Also, utilizing successfully optimized NIL process in
this work, photodetectors based on other semiconductors than SiC as Schottky photodiodes
in nano scale were pursued.

In summary, following tasks were involved as extended work in frame of this thesis:

- Designing and processing of micro scale SiC UV detectors using photolithography, met-
  allization and lift off
- Processing of NIL techniques in Electrum Laboratory
- Fabrication of nano scale GaSb, Si, InSb and InAs quantum dots (QD) devices using
  NIL

Due to success and great performance in the fabricated micro scale SiC UV detectors
an article was written and presented at the 16th Semiconducting and Insulating Materials
Conference (SIMC-XVI) in Stockholm, Kista 2011. This article can be read in Appendix A.
Difference in device performance for different substrates also lead to a simulation work by
J.-K. Lim at Acreo. This article is included in Appendix B.

1.3 UV Detector Applications

The target for UV detectors are many. They can be used to observe naturally occurring UV
light such as from the sun and reflections from it, or by exposure from various UV light sources.
It is important not to mix UV reflection with fluorescence since pure UV reflection cannot be
seen directly by a human eye. What you usually can see when emitting UV radiation on for
example white colored materials, is fluorescence. The high energy UV radiation is absorbed
and reflected with less energy in the visible range. To actually see the pure UV light reflected
you need a UV detector.

Applications for UV detectors are many. There are for example flame detection systems
combining infrared (IR) and UV detection lower the rate of false alarms and also to characterize
what is burning. For instance, black body radiation from a thermal source can more easily be
sorted out. This kind of spectroscopy could also be used for military applications.

One way of water bacteria treatment is to illuminate water with high power UV light
which eliminates bacterias. These bacterias are also visible in the UV range, which make UV
detectors a good way of monitoring the water quality.

In astronomy it can be important to view distant objects in different wavelength ranges
such as UV. Stars, including our own sun, look very different in the IR, visible, UV and X-ray
ranges. Also in nature you can find variation in appearance looking in UV. Birds and insects
can for example see UV light, enabling them to see other colors in flowers, feathers and organic materials.

Bringing the UV photodetectors to nano scale should increase time response. Fast time response could be used for example in UV fiber optics to increase speed in data transfer.
Chapter 2

SiC Materials and Devices

This chapter will give the reader the basic information about the material silicon carbide needed for this project. The theory of the metal-semiconductor-metal (MSM) photodetector devices will be briefly described. MSM devices are based on Schottky diodes why they also are mentioned in this chapter, not to mix up with pn-diodes.

2.1 Silicon Carbide

SiC is a group IV semiconductor material, which is a hot topic nowadays. It has a lot of different applications in electronics and mechanics due to its properties and advantages. It is almost as hard as diamond (9-9.5 on the Mohs scale, 10 for diamond) and in low doping concentrations it is almost fully transparent visually. Electrical devices in this material can be operated at very high temperatures, over 500 degrees celsius. SiC is also very tolerant to heavy high energy radiation. This makes the material suitable for space applications where it would need no shielding mechanism, which otherwise increases the total mass of the devices. Low mass and high tolerance to heat and external radiation makes it perfect for extreme environments such as outer space. This is just one application and we could go on make the list very long.

Moreover due to its wide band gap SiC is very suitable for UV photo detection whereas it corresponds very well to the limit between visible and UV light, 400 nm. Therefore no external filters would be needed in order to block light in the visible range for the detector. Optical filters might also reduce the intensity of incoming UV light. The construction of a detector will be simpler and the fabrication process will therefore be cheaper, while the performance should be better.

In former projects at Acreo GaN has been used as semiconductor for MSM UV detectors. SiC is an indirect bandgap material while GaN has a direct band gap and usually direct bandgap materials are preferred as photo detectors. However SiC is a much more mature material when it comes to quality, both dislocation density and numbers of crystal domains are many order of magnitudes lower in SiC. Also the electron affinity is higher in GaN than in SiC making the Schottky barrier height smaller in GaN, resulting in a higher dark current.
2.1.1 SiC Polytypes and Properties

There exist different polytypes, or atomic arrangements of SiC. Commercially the most common are 3C-SiC, 4H-SiC and sometimes 6H-SiC. The two last mentioned have hexagonal (Wurtzite) structures while 3C-SiC has the cubic Zinc-Blende structure. All these polytypes consists of 50% Si and 50% C. The difference between the hexagonal polytypes is the stacking order, they are not purely hexagonal. Atomic layers are twisted in the crystal in a certain sequence, where the sequence is shorter for 4H-SiC than 6H-SiC. If we introduce 2H-SiC, this polytype would be purely hexagonal having the wurtzite unit cell. The unit cell for 4H-SiC would be two times as large in the vertical hexagonal crystal direction compared to 2H-SiC, while 6H-SiC three times larger. Some material properties of the polytypes are listed in Table 2.1.

<table>
<thead>
<tr>
<th>SiC Polytype</th>
<th>Bandgap at 300 K (eV)</th>
<th>Cut Off Wavelength (nm)</th>
<th>Electron Mobility (cm²V⁻¹s⁻¹)</th>
<th>Hole Mobility (cm²V⁻¹s⁻¹)</th>
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<tr>
<td>3C</td>
<td>2.36</td>
<td>525</td>
<td>&lt;800</td>
<td>&lt;320</td>
</tr>
<tr>
<td>4H</td>
<td>3.23</td>
<td>384</td>
<td>&lt;900</td>
<td>&lt;120</td>
</tr>
<tr>
<td>6H</td>
<td>3.05</td>
<td>407</td>
<td>&lt;400</td>
<td>&lt;90</td>
</tr>
</tbody>
</table>

Table 2.1: Important properties of SiC polytypes

All the polytypes listed in Table 2.1 have been used and examined in this work. From these data, it was believed that 4H- or 6H-SiC would be most favorable for UV detection. Both these polytypes have their cut off wavelength near the UV/visible limit. The mobility also seems to be higher in 4H-SiC which hypothetically makes it the most interesting polytype.

A total of five SiC wafers were considered in this project, one 3C-SiC (100) and one 3C-SiC (111) orientated with already grown epitaxial layers with a thickness of 1.2 micrometer on top of Si substrates. The remaining wafers were one 4H-SiC (0001) 4°, one 4H-SiC (0001) 8° and one 6H-SiC (0001) exact. 4H- and 6H-SiC substrates were used to grow corresponding SiC epitaxial layers according to the device structure design and they had a highly doped substrate.

2.1.2 Epitaxial Growth

To form a high quality SiC layer it will be grown on a SiC substrate by low pressure chemical vapor deposition (LPCVD), which is one of many techniques to grow a material monolayer by monolayer. To grow materials this way is called epitaxial growth. An investigation of 4H- and 6H-SiC was needed to choose what doping type and concentration to be used for good performance in the UV detectors. High mobility is one feature to look for. For both polytypes, p-type or n-type yields that increasing doping concentration reduces the mobility. This also agrees well with Mathieson’s rule, here written in terms of mobility,

$$\frac{1}{\mu} = \sum_i \frac{1}{\mu_i}$$  \hspace{1cm} (2.1)

which shows that the total mobility ($\mu$) is determined by several scattering processes, $i$. At constant temperature, here the mobility is directly related to the impurities, which
is caused by doping of the material. More impurities results in less mobility due to higher
scattering of electrons and shorter mean free path. So whichever doping type will be used it
is good to have a low doping concentration. However n-type has higher mobility than p-type
from which you can draw the conclusion that n-type is preferable.

The focus was set on the 4H-SiC substrates since the cut-off is well below the visible/UV
limit but still not too far away. n-type mobility was the highest among the investigated SiC
polytypes. One 2 inch 4H-SiC (0001) 4°, one 2 inch 4H-SiC (0001) 8° and one 6H-SiC (0001)
exact substrate were grown in this project. The doping level of the substrates in the 4H-SiC
was around 10^{19} \text{ cm}^{-3} and 10^{18} \text{ cm}^{-3} for 6H-SiC. With the focus to grow n-type 4H-SiC, 6H-SiC
was grown in the same run since it should be possible. The recipe is however more favorable
for 4H-SiC growth rather than 6H-SiC growth. Target thickness for the layers were 6 \text{ \mu m},
which takes several hours to complete. Epitaxial growth is performed in Electrum Laboratory
in Kista by Acreo in a hot wall reactor at 1600 degrees Celsius. CVD is performed at 75 mbar
with H_2 as carrier gas. HCl is used for increased growth rate, growth materials are SiH_4 and
C_3H_8 and a low amount of N_2 is used to ensure n-type growth. The amount of N_2 is low to
keep the doping concentration low.

2.2 Metal-Semiconductor-Metal Photodetector

2.2.1 Schottky Barrier Diode

When a metal is in contact with a semiconductor, the electrical behavior of the contact might
be ohmic or have Schottky diode characteristics. Usually when diodes are discussed the pn-
diode is of interest, where a built in voltage is formed between two different doped regions
within a semiconductor. On one side of the diode the doping is p-type and on the other n-type.
The doping concentrations of each region determines the built in or "turn on" voltage, where
the diode becomes conductive.

However for the metal semiconductor interface, depending on the magnitude of the work
function of the metal (\phi_m) and the electron affinity of the semiconductor (\chi_s), an ohmic or
a Schottky contact can be formed. The metal work function is the energy difference between
the vacuum level (E_{vac}) and the Fermi level of the metal (E_F). For the electron affinity
of a semiconductor the definition is the difference between the vacuum energy level and the
conduction band energy level (E_C) of the semiconductor. In an ideal case the transition
forms a Schottky barrier when the electron affinity of the semiconductor is smaller than the
work function of the metal. Figure 2.1 shows the important properties of the materials. The
difference between the conduction band of the semiconductor and the Fermi level of the metal
that determines the height of the Schottky barrier (\phi_B = \phi_m - \chi_s), when vacuum levels of
the semiconductor and the metal are aligned. In Figure 2.2 one can also see how the built in
voltage (V_{bi}) is formed by the band bending due to alignment of the Fermi levels. The built
in voltage can be written as:

\[ V_{bi} = \phi_B - (E_C - E_F) \] (2.2)
Figure 2.1: Band diagrams of metal and n-type semiconductor apart.

Figure 2.2: Band diagrams of a Schottky contact between metal and n-type semiconductor.
Since the built in voltage is a function of the Fermi level, it is important to know how the Fermi level changes. The difference between the Fermi level and the conduction band in a semiconductor can be described using the Boltzmann approximation:

\[ E_C - E_F = \frac{k_B T \ln \left( \frac{N_C}{N_d} \right)}{q} \]  

(2.3)

where the Boltzmann constant \( k_B \), temperature \( T \), effective density of states in the conduction band \( N_C \), the donor doping concentration \( N_d \) and the elementary charge \( q \) are used to express the difference between the conduction band level and the Fermi level of the semiconductor. Equation 2.3 can now be rewritten using the statement Equation 2.3 and by expanding the Schottky barrier expression \( \phi_B \) we get:

\[ V_{bi}(N_d) = \phi_m - \chi_s - \frac{k_B T \ln \left( \frac{N_C}{N_d} \right)}{q} \]  

(2.4)

\[ N_C = 4\sqrt{2} \left( \frac{\pi m^* k_B T}{\hbar^3} \right)^{3/2} \]  

(2.5)

Figure 2.3: The change of built in voltage as a function of the donor doping concentration in 4H-SiC.

Using values for a n-type 4H-SiC semiconductor the change in built in voltage due to change in donor doping concentration is shown in Figure 2.3. To do this it is necessary to calculate the effective density of states in the conduction band of 4H-SiC from Equation 2.5. However 4H-SiC is an anisotropic material, meaning that the effective mass is varies in different crystal directions. Also it has an indirect band gap and therefore we need to know
the conduction band density of states mass \( (m_{dos}^* = m^*) \), before the effective density of states in the conduction band can be calculated.

\[
m_{dos}^* = n_{cv}^{2/3} (m_l^* m_t^*)^{1/3}
\] (2.6)

Here \( n_{cv} \) corresponds to the number of conduction band valleys in an indirect band gap semiconductor and \( m_l^* \), \( m_t^* \) are the lateral and transverse effective masses due to anisotropy. Knowing the anisotropic effective masses of electrons in 4H-SiC \( (m_l^* = 0.29m_0, m_t^* = 0.42m_0) \) and that there are \( n_{cv} = 3 \) conduction band valleys [1], we can obtain the effective density of states in the conduction band using Equation 2.6.

\[
m_{dos}^* (4H-SiC) = 3^{2/3} \left( 0.29m_0 (0.42m_0)^2 \right)^{1/3} \approx 0.77m_0
\] (2.7)

We can now use this value to calculate the effective density of states in the conduction band of 4H-SiC by Equation 2.5. Here we need the Planck constant \( (h = 6.63 \times 10^{-34} \text{ Js}) \), the Boltzmann constant \( (k_B = 1.38 \times 10^{-23} \text{ J/K}) \), the result from Equation 2.7 where \( m_0 = 9.11 \times 10^{-31} \text{ kg} \) is the electron mass [7] and assuming room temperature \( T = 300 \text{ K} \). The effective density of states in the conduction band becomes \( N_{C}^{4H-SiC} \approx 3.32 \times 10^{18} \text{ cm}^{-3} \). Through this value it is now possible to make the plot of how the built in voltage varies with the donor doping concentration of 4H-SiC in a Ni\((\phi_{Ni} = 5.15 \text{ eV})/4H-SiC(\chi_{4H-SiC} = 3.17 \text{ eV})\) Schottky diode [5, 8], shown in Figure 2.3. Further on we are interested in what is called depletion region, which is the active region in the semiconductor where the photo response takes place.

**Figure 2.4:** Depletion region width vs. applied bias in a Ni/4H-SiC Schottky diode for several donor concentrations.

In our Schottky contacts we want to make the depletion region width \( (W) \) as large as possible. Electrons that are excited to the conduction band outside the depletion region will
not make it to the electrode before they are recombined in the semiconductor. The electrons excited to the conduction band within the depletion region can however make it to the electrode before recombination in the semiconductor and in this case we have photodetection. Figure 2.4 shows how the depletion region width changes with different doping concentration and applied bias ($V_{app}$). This relation is described by Equation 2.8 \[6\].

$$W = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{q} \left( V_{bd}(N_d) - V_{app} \right)}$$

Here $\varepsilon_r\varepsilon_0 = 10.03 \times 8.85 \times 10^{-12}$ Fm$^{-1}$ [3] is the permittivity for 4H-SiC and $V_{bd}(N_d) - V_{app}$ is the difference between built in voltage and applied bias as a function of the donor doping concentration. Increasing the depletion region width will make devices fully depleted even at low voltages, since the ones fabricated in this project will have similar or smaller structures compared to the depletion region at zero applied bias. For low n-doped 4H-SiC ($N_d = 10^{14}$ cm$^{-3}$), with $q = 1.60 \times 10^{-19}$ C and no applied bias, the depletion region width becomes $W \approx 4.74 \, \mu$m.

### 2.2.2 MSM Junction as Photo Detector

Now we know the characteristics of a metal-semiconductor junction, so let us have a look at the metal-semiconductor-metal (MSM) junction as a photodetector. In Figure 2.5 the basic principle is explained. The tilt of the model illustrates the downslope created from applied bias. To actually detect light we need the presence of photons with higher energy than the band gap. If that is the case and the energy is absorbed by an electron, it is allowed to travel through the conduction band of the semiconductor. Now the distance to the counter electrode and the life time of the conduction band electron play a role if it will get to the counter electrode before recombination in the semiconductor. If the carrier makes it to the counter electrode it can be measured as a current and therefore we have a photoresponse. Here we can also define the so called quantum efficiency which is the ratio of input effect from photons, divided by the electrical output effect. Ideal is of course 100 %, which means that all the present photon energy is transformed in to electrical energy.

However, if there are no photons with enough energy to emit electrons into the conduction band, there will still be a weak current passing through the junction. This current is called dark current and mainly from thermal excitation of electrons which is the origin of the noise current. The ratio between photo- and dark current is important in order to get a good signal to noise ratio of the device.
Figure 2.5: MSM device biased and exposed to photons.
Chapter 3

Lithography Techniques

The most common patterning technique for fabrication of micro scale devices today is photolithography. But since device density is increasing to get more and more devices in a small area, devices need to shrink. Today’s most advanced deep UV step lithography techniques produce high performance processors with line widths down to 32 nm [9], but there are many speculations about how far down optical lithography can reach. For next generation lithography there are several candidates such as electron beam lithography, X-ray lithography and NIL. However the outlook for electron beam lithography seems to be poor since patterns are created by a single beam of electrons, making the process very time consuming and expensive in large scale fabrication. But if a single master pattern is fabricated it can be replicated by the NIL technique, which is more promising for large scale fabrication. Here line widths down to 5 nm have been demonstrated [10], while it is a simple way to transfer the pattern both cheap and fast.

This chapter will go through the two lithography techniques used in this project, photolithography and NIL with focus on the latter.

3.1 Photolithography

This technique is widely used for almost all nano- and microelectronic fabrication these days, due to its simplicity and high throughput. The main principle is to expose a wafer prepared with photoresist to UV light through a photomask. Compared to a photography the result will be binary in terms of exposed or non-exposed regions. If the resist is positive exposed regions are soluble in a developer while non-exposed regions remain. As the name suggests a negative resist have the opposite behavior. When the mask pattern is transfered to the resist further etching can be done in order to transfer pattern to substrate.

The limitations of this technique is mainly the wavelength used to expose the resist, due to diffraction patterns. Basically it is hard to produce higher resolution than the wavelength used for exposure. Therefore it is suggested to use as short wavelength as possible, why photolithography mainly is performed in the UV region. In this project a so lift-off process has been used to fabricate micro scale MSM devices. This is described in further detail in Chapter 4 Fabrication of Micro Scale Devices.
3.2 Nano Imprint Lithography

3.2.1 Principles of NIL

The basic idea of the NIL process is simple, where a master stamp is physically pressed down onto a resist on the substrate. The resist will be cured by exposing it to thermal- or photo energy. When it has become solid, stamp can be removed and pattern transfer is complete. From here further etching steps, metallization or lift off can be performed. There exist thermal NIL, combined thermal and UV-NIL techniques, but in this project the UV-NIL process has been used where the resist is cured by exposing UV light through a UV transparent stamp as shown in Figure 3.2. The process is performed in a yellow room and resist is stored in darkness to avoid curing it before it has been used. Resist can be disposed as a droplet (Figure 3.1) or by spinning, forming a very thin homogeneous layer. The benefit to use a droplet is that you can apply small amounts locally where the pattern is found, while spinning a thin layer consumes more resist and might not be successful. However spinning the resist avoids the mechanism of physically pressing the resist out on the substrate that otherwise might result in inhomogeneous resist thickness. In Figure 3.3 stamp is released with the transferred pattern left on the wafer. Here the materials used must satisfy some conditions for the NIL process to be successful. The resist must have good adhesion to substrate in order to stay there, while the adhesion needs to be poor to the stamp to not get stuck. These properties will be discussed further in Section 3.2.5 Adhesion.

Figure 3.1: Droplet disposal. The stamp is then pressed against the surface.
Figure 3.2: The resist is cured by UV light.

Figure 3.3: Stamp is released from the surface, leaving the nano pattern in the resist.
3.2.2 NIL Stamp Fabrication by e-beam Lithography

To be able to fabricate the small nano patterns in a NIL stamp you can no longer use ordinary photolithography. This is beyond its limits since it is very hard to make smaller structures than the wavelength used. However there exists lithography techniques that can reach the nano scale such as e-beam lithography. The E-beam lithography technique can fabricate patterns below 15 nm, but the problem with this method is the low throughput. Fabrication is made by evaporating resist with a single electron beam by scanning it through the targeted pattern. For wafer scale production this would be impossible in long term since this is way to time consuming for making a profit. But if a single wafer is produced with e-beam lithography the pattern can be replicated with the NIL technique, which is much faster and cheaper. Basically NIL share the same physical limits as e-beam lithography. Since NIL stamps are dependent on e-beam lithography, they are expensive to fabricate. But on the other hand the stamp can be used thousands of times without having any larger defects.

3.2.3 Stamp Replication by NIL

Making a backup of a master stamp is a very good idea since they are is expensive and time consuming to fabricate. The loss of a master stamp because of disappearing or by damage could be devastating. Instead of making many stamps of the same type with e-beam lithography they can be copied by the NIL technique. Replicating stamps this way is rather simple and just like backing up critical data on a computer hard drive, the master stamp is not critical anymore if broken or lost.

To fabricate a copy you first need to make an imprint with the master stamp to create a mirror image. This mirrored pattern can either be used as a negative stamp for lift-off processes, or like in this case to make another imprint to create the copy of the master stamp. Since the pattern has been inverted twice in this process it should look the same as the master stamp.

3.2.4 UV Curable Nano Imprint Resists

There are a few ways to turn a liquid resist into a solidified polymer. The two common methods using NIL are UV exposure, thermal baking or a combination of both. In this project two types of UV curable resists have been worked with, PAK-01 and mrCur21. PAK-01 is fabricated by the Japanese company "TOYO GOSEI" and has been used in previous projects at Acreo as a nano imprint resist. Disposal is made by droplet or spinning. The polymer itself contains Si and makes it hard to etch. A pure oxygen plasma is not enough to etch the polymer, however a mixture of oxygen and SF$_6$ has proven to work fine in previous NIL projects.

mrCur21 is another UV curable polymer that was investigated in this project. It is manufactured by the German company "micro resist technology GmbH". It does not contain Si like PAK-01 and is therefore easier to etch. However the mixture of oxygen and SF$_6$ was preferred during this project even though the etching rate is very fast. Disposal is done by droplet or spinning. Detailed user instructions are included and it can be mixed with a thinner to create a 100 nm thin layer by spinning.
3.2.5 Adhesion

When the stamp is removed from the cured resist, the patterned NIL resist should stay on the substrate. If the adhesive force to the stamp is larger than that to the substrate, the patterned nano features cannot be transferred properly. It turns out that the NIL resist may partly stuck on the stamp side, or in worst case the stamp and the substrate could not be separated. In such case, the stamp has to be cleaned, and this step is rather time consuming. The adhesive force on the stamp or substrate is govern by surface energy between the stamp (or substrate) and the NIL resist. High surface energy provides a hydrophilic surface and have better adhesion, in contrary a lower surface energy causes hydrophobic surface and results in less adhesion. In this work the substrates surface energy was modified by applying adhesive promoting layer to ensure good contact of patterned nanostructures on the substrate after the NIL process. To form a hydrophobic surface on the stamp side an anti sticking layer (ASL) was utilized to solve the potential problem of NIL resist remaining on the stamp.

Anti Sticking Layer

The ASL that is applied to the stamp surface is very thin, just a mono layer of the molecule used. it is recommended to use some sort of fluorocarbon since these chemicals tend to have very low friction and almost no materials get stuck to them. One example of fluorocarbon is TEFLOM which is commercially found in almost every frying pan nowadays. A chemical called trichloro(1H, 1H, 2H, 2H-perfluorooctyl)silane \((\text{C}_8\text{H}_4\text{Cl}_3\text{F}_{13}\text{Si})\) was investigated since the resist provider "micro resist technology GmbH" recommends it as a anti sticking agent. However this chemical was not tested enough to be in the fabrication process. Instead another anti sticking agent that have similar properties which is called chlorotrimethylsilane \((\text{C}_3\text{H}_9\text{ClSi})\) was used. It has been used in earlier NIL projects successfully at Acreo [1] and that is the main reason it was used in this work as well.

To apply the chemical, the stamp and the chemical needs to be in an oxygen free atmosphere since chlorotrimethylsilane is very flammable and a strong oxidizer. The stamp is loaded into a wafer box, a bit larger than the stamp itself, with about 5-6 drops from a pipette around it inside the box. Now the wafer box should be sealed for 10 minutes. The drops of the chemical will be evaporated. Its vapors will grow a monolayer on all surfaces inside the box, including the stamp.

Adhesion Promoter

To ensure a good contact between the resist and the substrate, resist providers recommend that an adhesion promoter should be used. This layer should be as thin as possible since additional materials makes etching processes more complicated. In this project a chemical called mr-APS1 from micro resist technology was investigated. The substrate is coated with spin coating at 5000 rpm for 60 seconds and then baked at 150 degrees Celsius for another 60 seconds. A 20 nm thick layer of adhesive promoter will remain on the surface ready to use. However the adhesion promoter was never needed for the fabrication in this project, the contact between substrate and resist was good enough. Cleaning of substrates by acetone, 2-propanol and a quick \(\text{O}_2\) plasma cleaning etch step was performed. No further pretreatment was necessary.
Chapter 4

Fabrication of Micro Scale Devices

As described in Section 1.2 Extended Work, micro scale devices were fabricated to be able to compare performance when going to nano scale. To investigate the performance of micro scale devices more detailed device properties can also be obtained, in this case comparison between different SiC polytypes with different finger spacing and finger widths of the MSM devices.

The fabrication process of the micro scale devices has been designed together with experienced personnel in the SiC research field at Acreo. It describes how the process is done after epitaxial growth step. Therefore it will be given that before this process is performed, the substrates already have their designed epilayers. Chapter 4 covers fabrication and design of the micro scale MSM photodetectors.

4.1 Fabrication Process

4.1.1 Cleaning

Before any fabrication process is made on the substrates they need proper cleaning. A bath in 5 % HF for 5 minutes will dissolve most of the contaminations on the substrate surface which might have got stuck there after the epitaxial growth. Rinse with DI-water and nitrogen blow dry follows. This should be performed immediately before next step in the process to minimize further possible contaminations.

4.1.2 Anti Reflective Coating

First a thin layer of silicon dioxide (SiO$_2$) will be applied in the fabrication process. This has two purposes. Since SiO$_2$ is an insulator the layer will prevent leaky currents on the surface in the final devices, for example due to contaminations. Also, we will design the thickness ($d$) of this layer is calculated to fit constructive interference for a specific wavelength, $\lambda = 365$ nm. This will increase the intensity and minimize reflection of the light in this wavelength region [11]. The specific wavelength has been chosen since our UV-LED used to carry out photoresponse measurements has its peak intensity at 365 nm. The result from this anti reflective coating should be a stronger signal for a certain amount of illuminated light, giving the detector a higher sensitivity. To optimize the thickness of this layer we use the following equation that describes constructive interference for such layer:

$$4dn \cos \theta = m\lambda$$  \hspace{1cm} (4.1)
For SiO\(_2\) the refractive index is \( n = 1.6 \) \[^{12}\] and if the incident angle of incoming light \( \theta \) to the device is assumed to be close to zero. Here we also focus on the first order interference \( m = 1 \) since we just want to increase one specific wavelength. Using these values we get:

\[
d = \frac{\lambda}{4n} = 57 \text{ nm}
\]

(4.2)

The SiO\(_2\) layer is grown on top of the SiC epitaxial layers by CVD and characterized by light interferometry to determine that the target thickness has been reached.

![Deposition of oxide layer](image)

**Figure 4.1:** SiC substrate with epilayers and SiO\(_2\).

### 4.1.3 Photolithography Patterning

In this step a lift off resist was spun on the wafer and soft baked, forming a layer of 2 \( \mu \text{m} \) resist. Patterning is done by conventional UV photolithography through a photo mask and developed to create openings and reach the SiO\(_2\) layer (Figure 4.2). A dry etch is then performed to make the SiO\(_2\) in the openings vanish while keeping the resist and SiO\(_2\) elsewhere (Figure 4.3).

![UV lithography patterning](image)

**Figure 4.2:** Patterning of the resist with a photo mask.
4.1.4 Metallization

To form a Schottky barrier on SiC the properties of the metal must satisfy a specific condition. The difference between vacuum and Fermi level in the metal must be greater than the electron affinity in the semiconductor, otherwise the contact will be ohmic. It is also better if the difference between these energy levels is as large as possible to minimize dark current. The most common metal used for SiC to form Schottky contacts is Ni, which should not be annealed. Annealing of Ni on SiC at 950 °C can form NiSi$_2$ with graphene layers underneath, this usually results in an ohmic or leaky Schottky contact [13].

There are two conventional ways to deposit the metal, by sputtering or e-beam evaporation. Sputtering is performed in vacuum pumped chamber by applying high electrical fields through the metal source, dislocating the atoms at the surface. The atoms will travel through the vacuum and end up on the substrate surface forming a metal layer. E-beam evaporation is performed in high vacuum by focusing a high energy electron beam at the metal source, heating it up and evaporating it. The metal gas will travel free in space until it hits any
surface and will stick there. In this fabrication process the sputtering technique was used. It was thought that too high energy might damage the lift-off resist. For the 4H- and 6H SiC samples 100 nm of Ni with 50 nm gold on top was deposited. Attempts to form Schottky contacts on two different 3C-SiC (111) and (100) samples was also performed. Here Pt was used as metal and the only way available to deposit it was with the e-beam evaporation tool. A 100 nm thick layer of Pt was formed on these substrates.

4.1.5 Lift-off

An acetone ultrasonic bath is performed to remove the metal parts with resist underneath. This step takes 1-24 hours to perform and when it is complete, the wafer should be rinsed with DI-water. A cross section of the final devices is shown in Figure 4.5.

4.2 Fabricated Micro Scale MSM Devices

Micro scale MSM devices where fabricated on 4 substrates, one 4H-SiC (0001) 4°, one 6H-SiC (0001) exact, one 3C-SiC (100) and one 3C-SiC (111). The 4H- and 6H-SiC has 57 nm of ARC with non annealed 100 nm Ni plus 50 nm gold on top as metal contacts on front side. Backside of these substrates where partly covered by 100 nm Ni annealed at 950 °C for 1 minute to form ohmic backside contacts. This enables front to back measurements making it possible to make C-V measurements and front to back I-V analysis. The two 3C-SiC pieces also had an ARC of 57 nm, but with 100 nm thick Pt contacts annealed at 500 °C for 5 minutes. No back side contact was made on these substrates.

The active device area (A_{dev}), metal finger width (w) and finger spacing (s) in one chip region varies from device to device. For some devices contacts are symmetrical, while the others share contacts on one side as shown in Figure 4.6. Device specifications are shown in Table 4.1 where the device type number is related to the finger width and l corresponds to the finger length. The important parameters are also shown in a sketch in Figure 4.7.
Figure 4.6: Mask design at chip level.

Figure 4.7: MSM device sketch.
Table 4.1: Specifications of micro scale MSM devices investigated in this work.

<table>
<thead>
<tr>
<th>Symmetric device type</th>
<th>Finger width (µm)</th>
<th>Finger spacing (µm)</th>
<th>Finger length (µm)</th>
<th>Number of fingers</th>
<th>Active device area (µm²)</th>
<th>Electrode (µm²)</th>
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<th>Finger spacing (µm)</th>
<th>Finger length (µm)</th>
<th>Number of fingers</th>
<th>Active device area (µm²)</th>
<th>Electrode (µm²)</th>
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<td>2x6</td>
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</table>

Figure 4.8: Optical microscope image of a symmetric MSM device on 4H-SiC.
Fabrication for all 4 pieces of SiC was successful and most devices were visually well defined. In Figure 4.8 we can see one of the smallest features, where the finger width is 3 μm and the spacing between them is 2 μm and they are all well defined.
Chapter 5

Fabrication of Nano Scale Devices

The technology used to fabricate nano scale devices in this project is NIL. This chapter will cover the whole process in detail, give some insight in issues that may arise during fabrication. Device specifications and some results of fabricated devices seen through an optical microscope are also included here.

5.1 Preparation

Figure 5.1: Cleaning of the surface with diluted hydrofluoric acid.
5.1.1 Cleaning

Just like in the micro scale fabrication process, the substrates need proper cleaning. A bath in 5 % HF for 5 minutes will dissolve most possible contaminations on the substrate surface, which might have got stuck there after epitaxial growth. This process is illustrated in Figure 5.1 where a schematic cross section of the substrate and the participating molecules are visualized. Rinse with DI-water and nitrogen blow dry follows. This should be performed immediately before next step in the process to minimize further possible contaminations.

Here it can also be mentioned that if any of the further process steps should fail the substrates might need to be cleaned again. The same cleaning process just described will make anything fabricated on top of the substrate vanish completely. Both the imprint resist and Ti that is used as metal dissolves in matters of seconds with HF treatment. This is therefore a quick and cheap process if you need to reset the work.

![Figure 5.2: Map of measure points used to determine thickness after each adjustment. The black and white region in the middle illustrates where the nano patterns of the device stamp are located.](image)

5.1.2 Stamp Mounting

This step really needs to be prepared in advance, since it can be very time consuming. The mounting is needed because the nano imprint tool, EVG-620, which has been used is only configured for 4 inch wafers. The device stamp that has been used is a 2 inch quartz glass wafer and therefore it needs mounting on a larger wafer. As a carrier wafer a UV transparent borosilicate glass (Pyrex) wafer is used. To stick the stamp together with this carrier a UV transparent wax is used. But before mounting of the stamp is done it needs to be cleaned and coated with an anti sticking layer (ASL).
The basic idea is to put the carrier on a hot plate at 80 °C. At this temperature the wax will melt and it is applied onto the middle of the carrier. Then the stamp is manually placed onto the wax carefully. It is hard to decide the exact amount of wax that should be used. Too small amount will make it difficult to adjust the stamp and too much makes the wax form larger clusters, increasing the probability for wax contaminations ending up on the stamp surface. This is the last thing we want to happen since you will need to clean and coat the stamp again. The stamp can be adjusted on the carrier by having it on the hot plate using sticks with cotton pads, gently touching the stamp surface to move it around. You should avoid the device pattern regions of the stamp doing this, otherwise you might damage them. The stamp should be roughly in the middle of the wafer and mounted as flat as possible. Flatness issues is probably the most time consuming step to correct. Even though a polished wafer looks flat it can differ in thickness in the micro scale, ±10 μm. Since the device stamp structure height is just 180 nm this is a big issue. If the thickness of cured imprint resist have too big slopes there will be problems transferring the pattern to the substrate when etching. Some part might have been totally etched away while other has not reached the substrate.

![Figure 5.3](image.png)

**Figure 5.3:** A 3D sketch of an adjusted stamp made in MATLAB. The ten measure points shown in Figure 5.2 has been used while the other points are approximated from the slopes between them. Unit for this sketch is meter.

When you have done adjustments the carrier, with the wax and stamp mounted to it, should be cooled down for a few minutes for the wax to solidify. Then the total thickness should be measured at several points to get an idea of the topography that the adjustments caused. If the thickness homogeneity is not satisfying, further adjustments and thickness measurements needs to be done. The most important aspect is that the device pattern region should not have a smaller thickness than any other region, as well as this critical area should not differ by more than 1 μm. When this has been achieved test imprints should be performed to see if the quality is good enough for fabrication. In Figure 5.3 a visualization of measurements done using the map in Figure 5.2 is shown. Even though the nano pattern region seems to be flat here the quality might not be good enough anyway. Only test imprints will show further details. AFM or other nano scale surface characterization techniques are not considered here.
since it would be more time consuming than a test imprint and it also might damage the pattern.

So how can we tell from a test imprint if the quality is satisfactory? To describe this Figure 5.4 will be used as a reference. Here you can see that the devices are located in a more or less color free region or a region that roughly only has one color. This is good, since colors arise from constructive interference from the cured resist. Meaning that one color corresponds to a certain thickness and change of color means change in thickness. The black-blue color that forms the circle closest to the pattern corresponds to the first order of interference. For the resist used, PAK-01, thickness has been calculated for this line to approximately 120-150 nm. A deeper discussion about colors and determining thickness is found in subsection 5.2.3 Residual Resist Etch by Dry Etching, where knowing the thickness in more detail is critical.

In Figure 5.4 the patterned region has none or extremely thin remaining resist layer surrounding the devices. This could be either good or bad. If the layer is too thin you might end up with no residual layer. This will give rise to adhesion problems. The contact area of the resist to the stamp will be always be larger than the contact area to the substrate, resulting in patterned structures getting stuck in the stamp rather than staying at the substrate when stamp is removed after curing.

![Figure 5.4: A picture captured from an optical microscope of a test imprint after satisfying adjustments of the stamp mounting.](image-url)
5.2 Fabrication Process

The target of this fabrication is to form top metal contacts with metal fingers by nano imprint lithography on SiC, to bring the features of the MSM photodetectors to the nano scale. Usually Ni is used as a metal with SiC for Schottky contact, since the adhesion is good and the Schottky barrier height is rather high. However a lift off process was not possible since no suitable stamp was available and there was no time to fabricate one either. Selective etching was therefore needed and that is very hard using Ni as metal. Instead Ti was used which has a slightly lower Schottky barrier height, but it has been processed in selective etches with nano imprint at Acreo before with good results.

Active device areas will be of different types with varying metal finger width and spacing, forming rectangular and circular shapes. This will give a good base for investigating effectiveness for different geometries of the devices. The smallest features in any of these devices are 50 nm.

5.2.1 Metallization

In this step a layer of 50 nm Ti will be deposited onto the substrates by e beam evaporation, see Figure 5.5. The homogeneity of this layer is very good and deposition is accurate in orders of Å. It would be more safe have a thicker Ti layer because the final device needs to be touched and this thin they will be very fragile. By using a thicker layer, difference in etch rate is not good enough to ensure that the pattern will be transferred to the substrate. The tool used
needs to pump down to high vacuum using a cryo pump. Reaching the working pressure of $5.0 \times 10^{-7}$ mbar takes 2 hours before process can be done.

5.2.2 Nano Imprint Lithography

Before the imprint is carried out, low energy 5 minute oxygen plasma at 150 W will be performed. This step has proven to increase adhesion between imprint polymer and substrate. Dispense of PAK-01 is made by applying a very small drop at the substrate surface in the region where the devices will be formed, when stamp is in contact. The size of the drop when applied should not be larger or smaller than 2 mm for best result. More resist will give a thicker layer, perhaps too thick to transfer the pattern properly by etching. Less resist can result in no residual layer around the pattern, which makes the cured resist to go with the stamp rather than staying on the substrate surface. Also too small amount may not fill out the patterns.

There is no aligning needed, so the imprint is now ready to be carried out. An exposure dose of 520 mJ, which corresponds to 40 seconds in the EVG-620 nano imprint tool used, has proven in former projects enough to cure the imprint polymer with a satisfactory result. Over exposure should not be a problem, but it can lead to different etching rates later on. After exposure stamp and substrate are carefully separated to avoid damaging the pattern.

5.2.3 Residual Resist Etch by Dry Etching

![Figure 5.6: Dry etching of the remaining resist down to the metal by plasma with gases SF$_6$ and O$_2$.](image)

After the nano imprint step there should be a thin layer of resist remaining around the devices. However, to transfer the imprinted pattern it is necessary to etch down remaining resist to
the metal. Here it is very important to know the thickness of the remaining resist and etching rate to accurately process the sample. To measure the thickness one can use a thin film interferometry tool. Knowing the refractive index of the cured resist \( n = 1.508 \) it is possible to examine constructive interference for wavelengths to determine thickness. There was no such program for the tool used though and there was no knowledge or time to investigate how to make a new program, so a similar already existing program was used that originally designed to measure film thickness of SiO\(_2\) on a Si substrate. The main difference is that the refractive index of SiO\(_2\) is slightly higher \( n = 1.6 \), but since it is almost the same it can be used for giving an approximation of the thickness. Looking at Equation 4.2 one can see that the increase of the refractive index will give a smaller thickness. This is good since it will reduce the probability of over etching from calculations of etching time knowing the thickness and etch rate. It is better to make two or more runs of etching being on the safe side, rather than over etching which might destroy the pattern.

5.2.4 Metal Etch

Wet Etch of Ni

Figure 5.7: Patterned resist on top of the metal before wet etch.

Since Ni is a good metal for Schottky contact with SiC a few recipes for etching Ni was investigated. In order for this etching process to work, the difference in etching rates between Ni and PAK-01 must be considered. A 50 nm layer of Ni needs to be etched away faster than a 180 nm layer of cured imprint resist PAK-01. The problem is that the acids or acid mixtures used to etch Ni are very strong. Phosphoric acid (H\(_3\)PO\(_4\)), nitric acid (HNO\(_3\)) and aqua regia (HCl:HNO\(_3\) - 10:1) etched away the imprint polymer rapidly. The acids had similar
behavior, they lifted the resist from the surface before it was etched away making it impossible to transfer the pattern. However a more gentle and suitable recipe was investigated consisting of a mixture of phosphoric acid, nitric acid, acetic acid and DI-water with the ratio 3:3:1:1. This mixture has a very temperature sensitive etching rate, but at 34 °C the etching rate was found to be around 1.1 nm/s. The etching of PAK-01 was much slower for this recipe, but even though this was the best attempt to wet etch Ni the result is clearly that it does not suit nano scale device fabrication. Device pattern before wet etching is shown in Figure 5.7 and after in Figure 5.8.

![Image of device pattern before and after wet etching](image)

**Figure 5.8:** Remaining metal structures after wet etch.

The etching time for the device that is shown in Figure 5.8 was 45 seconds. It was the only device that one could be recognized from the stamp pattern after this process, so the conclusion is that wet etching of Ni is not an option. Instead the metal was switched to Ti which has been used to fabricate similar devices on GaN in earlier project.

**Dry Etch of Ti**

Since no suitable recipe to etch Ni was found, Ti would have to be used instead. It has been used in the same fabrication process before, also dry etching of this metal has been well optimized. The dry etch is performed with O₂, N₂, BCl₃ and CF₄ gases with forward power of 600 W with the P5000 tool in Electrum laboratory. Etching rate is fast so only 13 seconds is needed to etch down the metal layer to the epitaxial layers. This recipe does also etch the resist very fast but only two times as fast as the Ti. Since the Ti thickness is 50 nm and the resist thickness 180 nm, there is no harm done if the sample should be slightly over etched.
5.2.5 Resist Stripping by Dry Etch

When the metal etch is complete there should be some remaining resist on the MSM devices if not strongly over etched. This must be removed in order to measure the devices at a probe station since the imprint resist PAK-01 is insulating. To determine how thick this layer is AFM is used. It is known that the metal thickness is 50 nm, so any value that is larger in step height from metal finger to substrate is considered as remaining resist. When the step height is determined the same process as in section 5.2.3 is performed, where the etch rate of PAK-01 roughly is 5 nm/s. This etching process is not harmful to the Ti, so a small over etch can be done to make sure that the resist gets stripped properly. This completes the nano fabrication process and the MSM devices are now ready for measurements. An optical microscope image of final devices is shown in Figure 5.11 and a cross section model image in Figure 5.12.
Figure 5.10: Dry etching to strip any remaining of the resist.

Figure 5.11: Complete nano devices with varying finger width and finger spacing.
5.3 Fabricated Nano Scale MSM Devices

Nano scale MSM devices have successfully been fabricated on four substrates, 4H-SiC (0001) $8^\circ$, Si, InSb and on InAs quantum dots (QDs). However the main focus has been on 4H-SiC. Visually they where all a success, the throughput of devices where close to 100 %. The big difference from the micro scale devices is that there is no back side contact, no ARC coating and the metal used is Ti instead of Ni which unfortunately reduces the Schottky barrier. Figure 5.13 illustrates the stamp imprint and it is the 2 lower rows in the device matrix that are of interest. These devices are shown magnified in the bottom of the this figure. Device specifications of these devices are shown in Table 5.1 and one can refer the different parameters to the sketch in Figure 4.7 for rectangular shaped devices, or Figure 5.14 for circular shaped devices.
Figure 5.13: Map of devices from the 2 inch stamp.

Figure 5.14: Sketch of circular shaped nano MSM devices.
### Table 5.1: Nano scale MSM photo detector specifications.

<table>
<thead>
<tr>
<th>Device No.</th>
<th>Finger width (nm)</th>
<th>Space (nm)</th>
<th>Length (µm)</th>
<th>Finger numbers</th>
<th>Electrodes (µm²)</th>
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<td>2x8</td>
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</table>
Chapter 6

Characterization of Devices

Micro scale MSM devices were fabricated on 3C- 4H- and 6H-SiC and nano scale on 4H-SiC, Si, InSb and on InAs QDs by nano imprint lithography. In this thesis report the focus of device characterization will completely be on 4H-SiC and 6H-SiC. Unfortunately the MSM devices on both 3C-SiC substrates formed ohmic instead of Schottky contacts, why these results are not discussed further. Si MSM nano devices have been demonstrated before, while InSb substrate and InAs QDs are for infra red wavelength detection and should be analyzed in future work.

In this chapter the characteristics of the devices are analyzed in physical, electric, optical and electro-optical aspects.

Figure 6.1: An array of 2 by 5 MSM photo detectors by SEM capture.
6.1 Material Characterization

To characterize the material several techniques has been used for different purposes. Optical microscopes have their limits due to optical wavelengths so both SEM and AFM has been used to analyze size of the devices. Also to determine the doping concentration and type, C-V measurements have been performed.

6.1.1 Scanning Electron Microscopy

Surface characterization at nano scale is impossible to do by traditional optical microscopes, since the size of the optical wavelength is a limit (400-700 nm for the visible spectra). However one can achieve higher resolution by using an electron beam as its wavelength can be much shorter; this advantage is used in Scanning Electron Microscopy (SEM). The drawback with this technique is that the energy density of the electron beam needs to be extremely high in order to give resolution at nano scale. It is very likely that the exposed material might be locally evaporated where the beam is too focused. The technique is anyway rather fast and captures black and white images with good quality. In Figure 6.1 a SEM capture is shown of some of the micro scale MSM photo detectors.

![Figure 6.1: Cross section SEM capture of 4H-SiC epitaxial layers.](image)

SEM was also used to produce cross section images of the fabricated devices. The micro scale devices where diced into chips by cutting with a diamond blade and Figures 6.3 and 6.2 shows how the 6H- and 4H-SiC chips look from the side. One can determine the thickness of the epitaxial layers of both polytypes here, roughly 8.7 μm for 4H-SiC and 6.5 μm for 6H-SiC. The value for 4H-SiC seems reasonable since 2 buffer layers were grown before the 6 μm of low
n-doped epitaxial layers. Regarding 6H-SiC we already knew that since it was grown in the same run as the 4H-SiC samples, the growth rate was not as favorable making the thickness smaller here.

Figure 6.3: Cross section SEM capture of 6H-SiC epitaxial layers.

6.1.2 Atomic Force Microscopy

The 4H-SiC samples turned out to have a very smooth surface after epitaxial growth. This is because they had been polished with 4°, 8° off the hexagonal c-axis and the growth is actually performed best on edges, which here consists of quantized arrangement of the atoms or the lattice constant. We could not find any roughness in optical microscope and even with the AFM it was very hard to detect any steps corresponding to the lateral lattice constant, roughly 10 Å. But the 6H-sample was grown on axis, which makes the growth more random and the result turned out to be a rough surface. Compared to the 4H-SiC epitaxial layers we could actually see this roughness in an optical microscope. It is however better shown in Figure 6.4 and from that measurement the lattice constant of 6H-SiC of 15 Å could be roughly confirmed.
6.1.3 Doping Profile

To determine the doping profile one can use capacitance-voltage (C-V) measurements and from the slope of the curve get doping type and concentration at a certain depth from the surface. The target for the 4H-SiC epitaxial layers were as mentioned before 6 \( \mu \text{m} \) of low n-type doping, \( 5.0 \times 10^{14} \text{ cm}^{-3} \). The result showed in Figure 6.5 shows that the n-type doping concentration was even lower, \( N_d = 10^{14} \text{ cm}^{-3} \).

However the 6H-SiC epitaxial layers raises some questions. The doping concentration turned out to be higher, around \( 10^{16} \text{ cm}^{-3} \), but it also turned out to be p-type. We can expect more contaminations in 6H- than 4H-SiC since the growth recipe was favorable for the 4H n-type polytype. But it must be that the 6H-SiC substrate was p-type rather than n-type. p-type contaminations from substrate must have been diffused into the epitaxial layers while growing them. The doping of the 6H-SiC is anyhow from Figure 6.6 determined to be \( N_a = 10^{16} \text{ cm}^{-3} \).
Figure 6.5: Doping profile of n-type 4H-SiC epitaxial layers.

Figure 6.6: Doping profile of p-type 6H-SiC epitaxial layers.
6.1.4 Optical Characteristics of SiC Epitaxial Layers on Substrates

Before an oxide layer was deposited, optical absorption and transmittance measurements of the grown 4H- and 6H-SiC samples were performed in the IMAGIC lab at Acreo. As seen in Figure 6.7 both are partly transparent for visible light. When SiC is pure from contaminations it should be fully transparent in the visible range, it is the dopant that gives it color. The 4H-SiC substrate has a higher doping level than in 6H-SiC making it brown/yellow in color. Figure 6.8 indicates this to be valid since violet, blue and green colors are absorbed more than yellow. Here we can also clearly see the visual range transparency of 6H-SiC with the absorption cut-off corresponding well to the cut-off wavelength from Table 2.1. This cut-off for 4H-SiC is not as clear and must depend on higher doping level in substrate.

![Fabricated devices on 4H-SiC (left) and 6H-SiC (right).](image)

**Figure 6.7:** Fabricated devices on 4H-SiC (left) and 6H-SiC (right).

![Optical absorption spectra for 4H- and 6H-SiC substrates with epitaxial layers. A-F corresponds to different measurement points.](image)

**Figure 6.8:** Optical absorption spectra for 4H- and 6H-SiC substrates with epitaxial layers. A-F corresponds to different measurement points.

The absorption measurements shown here were performed by shining "white light" on a sensor as a reference. Then the wafer is placed between the light emitter and the sensor so
that transmittance is measured. Absorption is here defined as light that does not transmit through the material, so any reflection is neglected as absorption. Also it is worth mentioning that neither emitter or sensor are linear in response or illumination, but they still show the optical properties well of the materials.

Attempts to determine the effectiveness of the ARC layer were also made but not successful. For example reflection measurements gave to weak signals compared to background noise, therefore we could not read out any information about how much reflection of the wavelength 365 nm had been decreased. Transmittance measurements through the wafer made no difference either from before. So there is no way from these measurements to tell how much or if the ARC layer improved the absorption of the wavelength 365 nm.
6.2 Spectral Response for Micro Scale MSM Devices

The spectral responsivity of the MSM photodetectors was measured by utilizing a Xe arc lamp and a monochrometer. The incident light was focused by a lens, and modulated with a chopper at 1kHz. Its power was calibrated using a UV-enhanced silicon photodiode. The photocurrent was measured using a lock-in amplifier. Typical responsivity curves as a function of incident wavelength of 4H- and 6H-SiC photodetectors with 3 μm finger width and 2 μm spacing are shown in Figure 6.9 for 4H- and 6H-SiC, with bias at 3 Volts. The cut-off wavelengths corresponds very well to calculated values from the band gap shown in Table 2.1. 6H-SiC has its cut-off just over 400 nm and 4H-SiC around 375 nm. Cut-off wavelength for 4H-SiC should be around 384 nm and it probably is, it just does not show in the measurements since the noise is too high. The higher doping concentration in 6H-SiC seems to play a role in larger current than in 4H-SiC.

![Figure 6.9: Spectral response for Micro Scale 4H- and 6H-SiC MSM Photodetectors.](image-url)
6.3 Photo Response and I-V Characteristics

I-V characteristics of dark current and photocurrent have been measured in darkness and by illuminating the samples with different UV light sources respectively. Mainly UV-LEDs have been used since they gave better control, stability and higher intensity than a UV lamp. The photocurrents shown in this chapter come from illumination with a 365 nm UV-LED with a flux density of 0.5 mW/cm$^2$ at a distance of 6 cm between light source and detector. All measurements have been performed at room temperature. The electric current shown in figures in this section are the absolute value of the actual current. Of course a negative bias gives a negative current, but taking the absolute value gives a better idea of the characteristics.

6.3.1 Micro Scale Devices

As mentioned before MSM devices were fabricated on 3C- 4H- and 6H-SiC. Unfortunately the MSM on both 3C-SiC substrates formed ohmic contacts, instead of Schottky. Their results are therefore not discussed any further. However n-type 4H- and p-type 6H-SiC both worked successfully with expected MSM I-V characteristics. It was mentioned that the photocurrent was larger in the 6H-SiC devices compared to 4H-SiC, which is seen here. I-V characteristics were done using a probe station with very sharp needles just touching contact pads of the devices on the top side. A voltage sweep from negative to positive bias was done to measure the current. Since the dark current was very low in 4H-SiC MSM devices special equipment, shielded and with signal filters had to be used to achieve the dark current. Photocurrent could be measured by a manual probe station since the signals were well above the noise level of that equipment, 100 pA. The results from symmetric contact MSM devices on 4H-SiC is shown in Figure 6.10 where 5 orders of magnitude between dark current and photocurrent is seen. For example similar devices, although vertical MSM instead of horizontal, reported from an Italian group [15] showed a magnitude difference of 2 orders for the same measurements. On the other hand their doping concentration of SiC was higher ($N_d = 2.7 \times 10^{15} \text{ cm}^{-3}$), so that could be one reason why our devices were an improvement. Also earlier projects at Acreo concerning GaN MSM UV detectors only showed one order of magnitude in difference. The improvement by using SiC should be that the material quality is higher since SiC epitaxy is more mature than GaN, also the electron affinity of 4H-SiC (3.2 eV) is lower than in GaN (4.1 eV). This material property makes it possible to have a higher Schottky barrier using 4H-SiC than in GaN, thus reducing the noise.
In 6H-SiC the photocurrent was 2 orders of magnitude higher than in 4H-SiC, but then also the dark current was higher. Figure 6.11 indicates that the difference is 4 orders of magnitude which still is very good, but not as good as 4H-SiC. However the strong photocurrent could be better for applications since the output signal is stronger. There could be many reasons for why the signal is so much stronger in 6H- than in 4H-SiC. For example according to the spectral response in Figure 6.9 the 365 nm UV-LED used is very near the limit of detection for 4H-SiC but well below the 6H-SiC cut-off wavelength. The quantum efficiency gets smaller the closer the wavelength gets to the cut-off.
Measurements of asymmetrical devices were also done and they showed different behavior than symmetrical devices. Figure 6.12 shows the I-V characteristics of two different devices with shared contact pad on one side, why they are geometrically asymmetrical. But it is clear that this also gives a different current response depending on negative or positive bias. When the electric field is towards the larger shared contact pad there seem to be influence from the other devices on the same contact pad. Metal reflects a big fraction of incoming photons but also absorbs a certain amount. This is thought to be the main reason for the larger current on one side of the I-V curve.

Something common for all the micro scale devices seen in the I-V characteristics is that the saturation voltage is very low, around or below 0.5 Volts. This means that the devices almost can be operated passive.
Figure 6.12: Photoresponse in asymmetric electrode type MSM.

6.3.2 Nano Scale Devices

The throughput of the nano scale devices was higher than expected. Measurements showed that 9 out of 10 devices showed MSM characteristics, the 10th was ohmic probably because contaminations. This is better than in any former project at Acreo regarding similar devices. Since the difference of the devices are so small the difference in current is hard to analyse, therefore Figure 6.13 shows an average of the two different geometrically shapes. They are
either circular or rectangular. The current from the circular devices was larger than in rectan-
gular devices although their active area is significantly smaller. The reason for this is unknown,
but it is thought that the empty area between the electrodes outside the circular fingers might
contribute. Since the distance between the electrodes is very small electrons might be able to
travel all way between them. The material is as mentioned before very low doped so scattering
is very low since the mean free path therefore is increased. Looking at the dark current it is
no way near as low as in the micro scale devices. Here the Ti in nano scale MSM play a big
role since its work function is lower than in Ni, reducing the Schottky barrier height. More
electrons have enough energy to pass through the lower Schottky barrier of the 4H-SiC/Ti
interface due to thermal excitations. Therefore we have a much higher dark current in this
case compared to the micro scale devices.

These MSM photodetectors have however been improved changing the substrate from GaN
to 4H-SiC and it is also the first time such devices has been demonstrated on SiC. In the GaN
MSM devices fabricated in an earlier project at Acreo it was even hard to see the MSM
characteristics due to the low photoresponse compared to the noise.
Chapter 7

Conclusions and Future Work

7.1 Conclusions

- We have designed and grown SiC epitaxial layers for UV detection. Two wafers of 4H-SiC with low n-type doping concentration and one 6H-SiC with low p-type doping concentration were successfully processed by LPCVD. The quality of the 4H-SiC epitaxial layers were very good, with a very smooth surface and a doping concentration of $N_d = 10^{14}$ cm$^{-3}$. 6H-SiC was grown on the horizontal axis and its surface not as smooth as the 4H-SiC epilayers. The doping concentration was measured to be $N_a = 10^{16}$ cm$^{-3}$ for the grown 6H-SiC epitaxial layers.

The outcome of the 4H-SiC epitaxial layers was as expected, which was not the case for the 6H-SiC layers. However the three wafers were grown in the same run with a recipe suitable for n-type 4H-SiC. Since it was believed that the 6H-SiC substrate also was n-type this SiC polytype should also be able to be grown with the same recipe. Unfortunately doping profile measurements after the epitaxial growth showed differently, that the substrate and epitaxial layers were p-type. A measurement before growing the layers would have shown this, but it was not considered at that time. Still the 6H-SiC wafer was a bonus to this project with main focus on 4H-SiC.

- Process development of NIL techniques in Electrum Laboratory has been done. Investigation of a new NIL resist, mrUVCur-21, was done to optimize a new and more stable fabrication process. Mainly to make better imprints since variation in thickness after imprint has been a great issue. This new nano imprint resist had already well developed instructions from the provider and a lot of time was spend on optimizing imprints from these recommendations. However it did not solve the thickness issue. Instead we came to the conclusion that the thickness issue rather origins from thickness variations in wafers and carriers used to make an imprint. Thickness measurements with accuracy of 1 µm showed that the thickness of stamp, carrier and substrates can differ up to 10 µm on different locations of the surface. In our setup all these components were used and also an additional layer of manually applied wax to attach the stamp to the carrier. Therefore it is very hard to make a good imprint with large scale throughput. To improve imprints in future, stamps should not need a carrier. Flatness of stamp and substrates also needs to have higher requirements regarding how much they can differ in thickness. Since stamp and substrate are in contact during an imprint, the difference in thickness
should not be larger and preferably much smaller than the height of the structures in the stamp.

Attempts to replicate a test stamp and the master stamp used in this project were performed. However this process was never fully developed for full functionality and reliability. We came to the conclusion that another type of anti sticking layer should be used for replicated stamps. An anti sticking agent was found for this purpose, but there was no time for further investigation here since it required a new more complex process for deposition of the chemical.

- Micro scale UV detectors in 4H- and 6H-SiC has successfully been fabricated with good results and performance. Compared to a previous project where MSM UV photodetectors here made in GaN the performance was improved regarding the signal to noise ratio, which is the same as photocurrent to dark current ratio in this case. There are several reasons for this, but we believe that it mainly has to do with material quality and the Schottky barrier height of the devices.

- Shrinking of 4H-SiC UV detectors from micro- to nano-scale has successfully been demonstrated using nano imprint lithography. This has not been done before on SiC, but in the previous project just mentioned it has been done using GaN as substrate. However the throughput in the device fabrication was increased and nano-scale MSM devices were also made on InSb and on InAs QDs for future investigation. The nano-scale MSM devices on 4H-SiC had a better signal to noise ratio compared to nano-scale MSM devices on GaN. The reason for this is believed to be the same as for the micro-scale devices just mentioned.

- Measurements that has been performed of fabricated MSM UV photodetectors concern electrical and optical performance, such as dark current, photocurrent and spectral response.

7.2 Future Work

- Devices should be optimized by deeper investigation of which combination of device geometry that gives highest efficiency by analyzing photocurrents.

- High resolution time response measurements should be performed of fabricated devices since it is believed that the nano-scale devices have a faster response than in micro-scale.

- 2D array should be fabricated for UV imaging.

- Development of the nano imprint lithography should be done. Especially regarding development of a fully functional stamp replication process and a lift-off process that suits NIL.
Bibliography


Appendix A

4H- and 6H-SiC UV photodetectors

4H- and 6H-SiC UV photodetectors

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In this work, wafer-scale 4H- and 6H-SiC lateral and vertical Schottky UV photodetectors (PDs) and arrays were fabricated, characterized and compared. The lateral type device was configured as a metal-semiconductor-metal (MSM) photodetector with different finger electrode widths and spacing between the fingers. The vertical type devices were formed utilizing the MSM electrodes as a top contact and a Ni contact on the wafer backside. Both types of device were fabricated on the same wafer, as seen in the abstract figure, where the transparent part of the wafer contains lateral devices and the opaque part contains vertical devices. This enables a direct comparison of the performance of the different devices types. The best fabricated PDs exhibited a UV to dark current ratio of about five orders of magnitude. The dark current was measured to be about 100 fA.

1 Introduction Silicon carbide (SiC) is a promising material for high-temperature and high-frequency electronic applications owing to its wide bandgap, high breakdown electrical field, high thermal conductivity and low thermal expansion properties [1]. The advantages of SiC in optoelectronic applications, such as UV detection and solar cells, make its future even brighter [1-3]. SiC devices are based on more mature material technology, in comparison with, for example, III-nitride technology. The defect density in SiC material is many orders of magnitude lower than in GaN material. This ensures sensitive device performance in various applications including combustion optimization, and air/water contamination monitoring.

Among many SiC polytypes, 4H- and 6H-SiC are regarded as the most suitable for UV detection, due to their good material quality and large band gap 3.23 eV (384 nm) and 3.05 eV (407 nm), respectively. The crystal structures of both 4H- and 6H-SiC are hexagonal. The difference between them lies in the stacking order of the SiC layers.

In this work we present the design, fabrication and evaluation of 4H- and 6H-SiC UV PDs. The epitaxial structures were grown on 4H- or 6H-SiC substrates using Acreo’s reactor situated in the Electrum Laboratory, Kista, Sweden. The fabricated devices were characterised by measuring their dark current and photocurrent under UV illumination. The spectral and transient photoresponse of the detectors were also characterized and compared. The fabricated PDs were shown to exhibit low dark currents with breakdown voltages higher than 120 V, good photoresponse and a high UV to visible rejection ratio.

2 Device design The MSM photodetector is a planar device consisting of two interdigitated fork-shaped contacts on the semiconductor surface, as illustrated schematically in Fig. 1 (a). It detects photons by collecting photoexcited electrons and holes that are generated between the fingers and then drift to the electrodes under the electrical field applied between the electrodes. Such detectors have
the advantages of low dark current, high-frequency response and low noise level. However, their quantum efficiency is limited by the finger metal electrodes, which shadow part of the optical area.

In this work, two series of MSM detectors were designed. The finger numbers were kept constant in one set, and the other set had a fixed detection area, as listed in Tables 1 and 2. This enabled an investigation into the optimum configuration of the MSM detectors. The width of the metal fingers was designed as 2 or 3 µm, and the spacing between the fingers as 2, 3, 6 or 10 µm. In the case of the constant area devices, the active area was calculated by subtracting the electrode area from the area defined by the red frame in Fig. 1 (a). The active area was arranged to be about 11000 µm² in the constant area cases.

![Figure 1](a) Schematic illustration of MSM PD, and (b) SEM image of a fabricated MSM PD with finger width of 3 µm and spacing 2 µm.

### 3 Device fabrication

The UV PDs were fabricated on two 2” SiC wafers. One wafer contained a 6.7 µm epilayer grown on a double side polished semi-insulating 6H-SiC substrate. The other contained a 7.5 µm epilayer on a highly conductive one-side polished 4H-SiC substrate. The epi structures were grown in a hot wall CVD reactor, where silane and propane were employed as precursors for the growth, and nitrogen as dopants. Purified hydrogen served as the carrier gas in the growth process.

Before device fabrication, the room temperature absorbance of the 4H- and 6H-SiC wafers were measured at normal incidence using a StellarNet EPP2000-UVN-SR spectrometer, and their absorbance spectra are shown in Fig. 2. There is clear cut-off at about 400 nm in the spectra for the 6H-SiC wafer, but not very pronounced (marked by a red arrow in Fig. 2) for the 4H-SiC. This is most likely caused by light scattering by the backside roughness of the single-side polished 4H-SiC substrate. The uniformity of the absorbance across the 2” wafers was examined with 5 mm spatial resolution. Fig. 2 also shows absorbance spectra from several positions from the wafer centre to its edge. These indicate a good uniformity for both 4H- and 6H-SiC wafers.

![Figure 2](Absorbance spectra of the 4H- and 6H-SiC wafers. The measurement points (A, B, C, D and E) were selected from the wafer edge to the centre.)

The interdigitated metal electrodes were formed by optical lithography, followed by metal evaporation of Ni/Au and lift-off. SiO₂, which was subsequently patterned between the finger electrodes, functioned both as a passivation and anti-reflectance coating layer. Fig. 1 (b) shows a SEM image of a fabricated MSM PD with a finger width of 3 µm, and 2 µm spacing.

The vertical type devices were fabricated utilizing the MSM electrodes as a top contact (by the same process as the lateral devices), and an Ohmic contact on the backside of the wafer. The backside contact was formed by sputtering 200 nm Ni, followed by rapid thermal annealing at 950 °C.

### 4 Device characterizations

A range of the single pixel PDs and their arrays were characterized electrically and optically using the measurement techniques detailed in following sub-sections.

#### 4.1 Photocurrent and transient response

The dark current of the MSM detectors was measured by a HP 4156A precision semiconductor parameter analyzer or...
Keithley 237 high-voltage measurement unit. The 4H-SiC devices had dark currents about 100 fA. The dark current of the 6H-SiC PDs was seen to be a few orders of magnitude higher as shown in Fig. 3.

The photocurrent as a function of bias was measured using a series of UV LEDs, at wavelengths of 255 nm, 285 nm and 365 nm. The incident light power density could be varied by adjusting the distance between the PD and the light source. The photocurrents of a 4H- and a 6H-SiC PD illuminated by a 365 nm LED with a power density of 0.5 mW/cm² are shown in Fig. 3. This reveals a high photocurrent in comparison with their corresponding dark currents over a wide bias range. A dark to UV ratio of almost four and five orders of magnitude was obtained for the 6H-SiC PD and 4H-SiC PD, respectively.

![Figure 3](image)

**Figure 3** Dark and photocurrents of 4H- and 6H-SiC UV PDs with finger width of 3 µm and spacing of 2 µm. Inset: transient response of the 6H-SiC PD under 365 nm or 255 nm UV illumination, respectively.

It is worth noting that both the dark current and photocurrent of the PDs exhibit a good symmetry at zero bias. This reflects the symmetry of the MSM electrodes formed by well-controlled device processing.

The photocurrent of various PDs listed in Tables 1 and 2 and their arrays were verified by the same measurement technique. The photocurrent of the PDs with a fixed number of fingers increased as the spacing increased from 2 µm to 10 µm. In contrast, the PDs with constant areas had similar photocurrents, even though the number of electrodes and the total device area differed.

The vertical PDs were characterized by utilizing the MSM finger electrodes as an anode and the rear side Ni contact as a cathode. Their dark currents and photocurrents exhibited typical Schottky diode behaviour, with the reverse-bias behaviour being similar to that in corresponding lateral devices.

The transient response characteristic of the fabricated PDs was also measured using the HP 4156A semiconductor parameter analyzer. The inset of Fig. 3 shows an example of transient response spectra obtained by measuring a 6H-SiC PD under UV illumination at 365 nm and 255 nm wavelengths. It shows good on/off response when the UV light is switched on and off, which provides confirmation of the good photoresponse of the fabricated PDs.

### 4.2 Spectral responsivity

The spectral responsivity of the PDs was measured by utilizing a Xe arc lamp and a monochrometer. The incident light was focused by a lens, and modulated with a chopper at 1 kHz. Its power was calibrated using a UV-enhanced silicon photodiode. The photocurrent was measured using a lock-in amplifier. Typical responsivity curves as a function of incident wavelength of 4H- and 6H-SiC PDs with 3 µm finger width and 2 µm spacing are shown in Fig. 4. The responsivity of the 6H-SiC PD is higher, and its peak responsivity occurs at a shorter wavelength than that of the 4H-SiC PD. The peak quantum efficiency (QE) of the 4H-SiC PD is about 30 % at 315 nm, while a QE over 100 % was obtained for the 6H-SiC PDs. This could be attributed to the existence of internal gain in the PD caused by charge traps at SiO₂ and SiC interface. The interface charge accumulation is optically promoted, and results in a Schottky barrier lowering effect.

![Figure 4](image)

**Figure 4** Photoresponsivity of the 4H- and 6H-SiC PDs at - 3V. Two reference lines indicate responsivity values having 100% (grey) and 50% (cyan) QE vs. wavelength, respectively.

### 4 Conclusion

The performance and design trade-offs of the 4H- and 6H-SiC PDs have been analyzed and compared in this work, providing valuable information for further improvement of device performance and for the design of next generation novel UV photodetectors.

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**References**

Appendix B

A theoretical and experimental comparison of 4H- and 6H-SiC MSM UV photodetectors

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A theoretical and experimental comparison of 4H- and 6H-SiC MSM UV photodetectors

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Abstract. This paper reports on fabrication and modeling of 4H- and 6H-SiC metal-semiconductor-metal (MSM) photodetectors (PDs). MSM PDs have been fabricated on 4H-SiC and 6H-SiC epitaxial layers, and their performance analyzed by MEDICI simulation and measurements. The simulations were also used to optimize the sensitivity by varying the width and spacing of the interdigitated electrodes. The fabricated PDs with 2 µm wide metal electrodes and 3 µm spacing between the electrodes exhibited, under UV illumination, a peak current to dark current ratio of 10^5 and 10^4 in 4H-SiC and 6H-SiC, respectively. The measured spectral responsivity of 6H-SiC PDs was higher compared to that of 4H-SiC PDs, with a cutoff at 407 nm compared to 384 nm in 4H-SiC PDs. Also the peak responsivity occurred at a shorter wavelength in 6H material. A high rejection ratio between the photocurrent and dark current was found in both cases. These experimental results were in agreement with simulation.

Introduction

Silicon carbide (SiC) is a very attractive material for UV photodetectors (PDs) due to its wide bandgap and high absorption coefficient in the UV region. Owing to its material maturity and stability, detectors utilizing 4H- and 6H-SiC (bandgap of 3.23 eV and 3.05 eV, respectively) have the advantage of a good photoresponse with a very low dark current, and can also operate in harsh environments. In recent years, SiC UV PDs have been the subject of many publications that demonstrate their potential [1, 2]. Different measures to improve the sensitivity of the devices have been investigated, such as the use of semitransparent electrodes [3], structural design [4] and avalanche detectors with novel embedded structures [5]. Also theoretical work which improves the absorption models for 4H-SiC at short wavelengths has been published [6]. In this paper, we compare the performance of 4H- and 6H-SiC MSM UV PDs by simulation and experiment, taking into consideration inherent material properties and optimization of the device performance.

Device design and fabrication

A top view of the fabricated detector is shown in Fig 1. The two terminal device consists of two interdigitated Schottky electrodes in the so-called back-to-back configuration. It detects photons by collecting photo-excited electrons and holes that are generated between the fingers and then drift to the electrodes under the influence of the electric field. The cross-section of the fabricated and simulated structure is shown in Fig 2. The optically exposed layer, in the case of the 4H-SiC PD, is a 7.5 µm thick epitaxial layer, with a doping level of 10^{14} cm^{-3} grown on a highly conductive one-side polished 4H-SiC substrate. In the case of the 6H-SiC PD, the epitaxial layer is 6.7 µm thick, with a doping level of 10^{16} cm^{-3}, grown on a double side polished semi-insulating 6H-SiC substrate.
Schottky contact electrodes were formed on the epitaxial layer by sputtering 100 nm of Ni. The electrode width and spacing, in the experimental structures, were 3 and 2 \( \mu m \), respectively.

**Fig 1.** Optical microscope image of a fabricated metal-semiconductor-metal (MSM) PD. **Fig 2.** Simulated and fabricated device structure of the MSM PD.

**Simulation results**

In this work, the photoresponse of 4H- and 6H-SiC MSM PDs has been simulated using MEDICI. The electrode width, \( w \), and electrode spacing, \( s \), were first optimized by simulation. The width of the electrode fingers was chosen to be 2, 3 and 4 \( \mu m \), and the spacing between the fingers was varied from 2 to 20 \( \mu m \). In order to simulate the photocurrent of the MSM PDs, the photogeneration, absorption, and refractive models from ref [5] were adopted. In particular, the absorption coefficient model derived for 4H-SiC in [6] was used. The same model was carefully modified in order to simulate the 6H-SiC devices. Schottky boundary conditions were applied for the surface metal contact.

**Influence of spacing and finger width.** In Figs. 3 and 4, simulated I-V characteristics under illumination and dark conditions are shown, respectively, for 4H-SiC MSM PDs with different values of \( w \). The I-V characteristics under illumination are simulated at a photon wavelength of 365 nm and photon flux of \( 9.19 \times 10^{14} \) photons/cm\(^2\)·s. The detector area is taken as 1cm\(^2\) in all calculations. The photocurrent is found to be directly proportional to the optically exposed area, and dark current is proportional to the area covered by the negatively biased metal electrode. This can also be seen in data from Figs. 5 and 6, where simulated photo and dark I-V characteristics are shown, respectively, for 4H-SiC MSM PDs with different \( s \) values. The photocurrent shows no dependency on the applied reverse bias, and increases from 2.98 to 6.13 \( \mu A/cm^2 \) when \( s \) is changed from 2 to 14 \( \mu m \). Analysis shows the photocurrent to be directly proportional to the absorption area in this range of \( s \) values. Dark currents increase slightly with increase of the applied voltage, and the rate of increase becomes smaller with decreasing value of \( s \).

The photocurrent displays a maximum at an optimum value of \( s \) as shown in Fig. 7, which is dependent on the doping of the epilayer, but not on the SiC polytype. The optimum values of \( s \) are 7 \( \mu m \) and 14 \( \mu m \) for the PDs with doping levels of \( 10^{16} \) cm\(^{-3}\) and \( 10^{14} \) cm\(^{-3}\), respectively. This is in good agreement with theory, considering that the difference in their space charge widths is about 7 \( \mu m \) (space charge widths of 1 \( \mu m \) and 8 \( \mu m \), respectively, at -6 V) and that the diffusion length for holes is about 10 \( \mu m \) in both cases.

**Photoresponse and comparison with experiment.** The photocurrent and dark current of the fabricated 4H- and 6H-SiC MSM PDs have been measured using a 365 nm LED with a power density of 0.5 mW/cm\(^2\). This revealed high photocurrents in comparison to the corresponding dark currents over a wide bias range, as shown in Fig. 8. The ratio of photocurrent to dark current is five and four orders of magnitude, respectively, as shown in Fig. 9. Furthermore, the difference between
the polytypes, is one order of magnitude in both the experimental and simulated structures. The difference between the experimental and simulated results is about two orders of magnitude, due to the higher leakage current of the fabricated PDs compared to the theoretical values.

The measured and simulated spectral responsivity of the PDs as a function of the incident light wavelength is shown in Fig 10. The incident light from a Xe arc lamp was used in these measurements. The responsivity of the 6H-SiC PD is shown to be 3-5 times higher than the 4H, and its peak value occurs at a shorter wavelength. The 6H-SiC PD also has a wider detection bandwidth (210 - 410 nm) as compared to the 4H-SiC (250 - 370 nm). The simulated photoresponsivity shows the same cutoff wavelengths (407 nm for 6H-SiC and 384 nm for 4H-SiC) as the measurements. The simulated photoresponsivity values and detection bandwidth at the low wavelength side of the spectrum differ from the measured values. The first is attributed mainly to the accuracy of the absorption coefficient model, and the second to the properties of the antireflective coating on the experimental structures which were not included in the model.

Summary

Efficient MSM PDs with high rejection ratio have been fabricated on both 4H- and 6H-SiC epilayers. Guidelines for further enhancement of the photosensitivity by design optimisation have been determined from simulations. The 6H-SiC PDs had 3-5 times higher responsivity and a wider detection bandwidth as compared to the 4H-SiC devices. At the same time they had a one order of
magnitude smaller photocurrent to dark current ratio, due to their higher dark current. These properties are related to the smaller bandgap of the 6H-SiC and poorer material quality.

The photocurrent was found to be proportional to the absorption area, over a range of s values below the optimum spacing value. The optimum spacing of the electrode was found to be 15 µm and 7 µm for the PDs with an epi doping level of $10^{14}$ cm$^{-3}$ and $10^{16}$ cm$^{-3}$, respectively, and independent of the polytype. The electrode spacing was found to have a dominant influence on the photocurrent compared to the width of the metal electrode. The dark current depended only on the width of the reverse biased electrode, and was found to be proportional to its area. The electrode width should be as small as possible in order to achieve a large photocurrent to dark current ratio.

References