

# TFE4575: LED lab

Brynjar Morka Mæhlum<sup>a</sup>, Thord Niri Gjesdal Heggren<sup>a</sup>

<sup>a</sup>Department of Physics, Norwegian University of Science and Technology, 7491 Trondheim, Norway.

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## Abstract

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## 1. Introduction

LEDs (Light Emitting Diode) are, as the name suggests, a type of electrical component producing light. They are widely used due to their low power consumption, long

lifetime, small size, and fast switching. LEDs are made up of strategically layered semiconductors and metals. Then, in order to produce a working diode, the wafer needs to undergo several process steps. Some of these can be photolithography, etching, deposition, and annealing. After, the LEDs should be characterized and tested, e.g. by scanning electron microscopy (SEM), optical microscopy and current-voltage (IV) testing.

## 2. Theory

### 2.1. LED theory

In its most simple form, a LED is a p-type semiconductor (SC) in contact with a n-type SC, i.e. a pn-junction. In the region close to the contact point of the two SC materials, electrons and holes will recombine. This leaves a negative charge on the p-type SC and a positive charge on the n-type SC, creating an electric field. The region where this electric field is present is called the depletion region, and will under normal conditions be free of charge carriers. When a voltage is applied over the pn-junction, electrons and holes are pushed into the depletion region where they recombine. This can either happen non-radiatively or radiatively, where the latter is the process that emits light.

### 2.2. Photolithography

Photolithography is used to print temporary micro- and nanoscale structures on a substrate. This is done by coating the substrate in a light-sensitive photoresist and strategically exposing it to light. The photoresist will then either harden or dissolve depending on the type. Negative resist gets insoluble in the developer when exposed to light, while positive gets soluble. As a consequence, the mask used with a negative resist must be the inverse of the desired structure, while with positive resist, the structure must be identical. The process should be done in a cleanroom, as it is very sensitive to contaminations. The following list gives the name and purpose of the eight main steps in the photolithography process:

1. **Cleaning:** Remove any contamination from the substrate.

2. **Spin coating:** Spin coat the photoresist on the substrate.
3. **Soft bake:** Bake the photoresist to remove any solvent.
4. **Exposure:** Expose certain areas of the photoresist to light. Eventually with mask alignment.
5. **Develop:** Develop the photoresist to remove the softened parts.
6. **Post exposure bake:** Bake the photoresist to initiate resist reactions for deep UV resists and enhance adhesion.
7. **Hard bake:** Bake the photoresist to remove any solvent. Not often needed.
8. **Inspect:** Optical inspect the photoresist to see if it is good.

Lift-off is a technique used to remove the photoresist from the substrate after metallization. When doing lift-off, it is most common to use negative resist. This is because only negative resist can achieve an undercut resist profile, which can improve the metall edges

Different photoresists need different baking parameters, spin speeds, developing times and exposure doses. These can also change for the same resist over time, when the resist is exposed to light, heat, humidity, and contaminations.

### 2.3. Contact Formation

LEDs need to have both a front and back metal contact. The purpose of the contacts are to provide a path so that current can be injected to the device. The back contact can simply be deposited on the whole back side of the wafer. The front contact however, needs to be patterned. This is because in order to reduce absorption losses, the contact area needs to be minimized while keeping the spreading resistance as low as possible. It is important to carefully chose the contact material, as it affect the electrical properties of the device. Also, the front side contracts should be made first, as the following steps may damage the surface.

### 2.4. Etching

Etching is a process of chemically removing material from a surface. The process can be divided into two categories - wet etching and dry etching. Wet etching uses a liquid etchant, while dry etching uses a gas etchant. In LED fabrication, etching is an important process step. Here, etching is typically used to remove strongly light absorbing layers or to electrically isolate different parts of the device.

### 2.5. Passivation

Exposed sides of the LED will result in high non-radiative recombination at the surface, which will reduce the efficiency of the LED. Also, exposed sides increases the risk of shorting the circuit. For those two reasons it is thus

necessary to coat the LED surface in passivation material, e.g.  $\text{Si}_3\text{N}_4$ . The deposition of this layer should be done by an isotropic deposition method to ensure that the layer cover both horizontal and vertical edges. One such method is plasma enhanced chemical vapor deposition (PECVD). The thickness of the layer should be such that the optical path creates destructive interference at the wavelength of the emitted light  $\lambda$ . This relation is given by

$$2d = \frac{\lambda}{n} \frac{3}{2} \quad (1)$$

where  $d$  is the thickness and  $n$  is the refractive index.

### 2.6. Characterization equipment

The characterization equipment used in this lab were optical microscope, SEM, profilometer, ellipsometer, and LED IV-testing. The theory and working principle behind these instruments are assumed to be known.

## 3. Methods

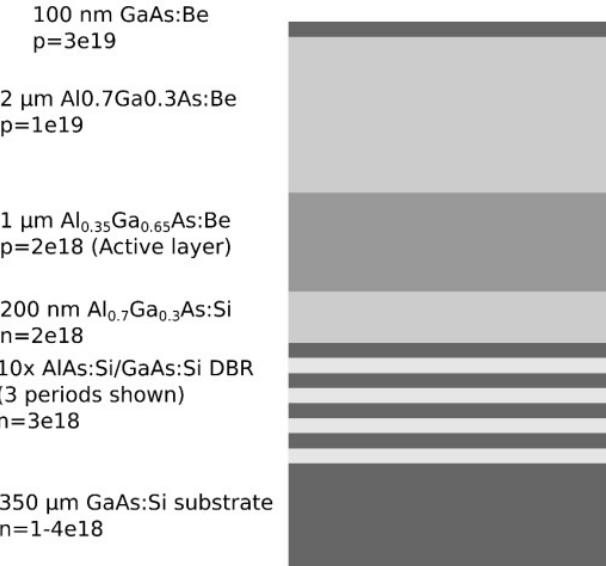
The LED sample with its metal layers shown in [Figure 1](#) was grown by the staff of the course and given to the student group. To form a working LED from the metal layer sample, the following steps were done at NTNU NanoLab:

1. Front contact formation
2. GaAs contact layer etch
3. Backside contact formation
4. Mesa etch, PECVD passivation deposition, and contact annealing
5. Planarization and passivation layer etch
6. Pad metallization

Each step was first done with a GaAs dummy sample to check that the process was working as intended. After the last step, the LED was ready for testing at a lab at IES, the Department of Electronic Systems at NTNU.

### 3.1. LED design

Different finger spacings and finger widths were tested. An overview schematic of the LED design is shown in [Figure 8](#). One LED was 1 mm x 1 mm. The bus bar for contact pad was 1 mm x 40  $\mu\text{m}$ . The bus bar connecting the fingers was 1 mm x 30  $\mu\text{m}$ . The fingers were 500  $\mu\text{m}$  long, with widths at 4, 8, 12 and 16  $\mu\text{m}$ , and finger spacing at 40, 60, 80 and 100  $\mu\text{m}$ . The second lithography layer was equal to the first, but scaled with a 5  $\mu\text{m}$  buffer everywhere to protect the fingers. The third lithography layer was for the mesa etch, and was a box around each LED with a 6  $\mu\text{m}$  buffer. The fourth lithography layer was for the etch of the passivation layer, and was just a 20  $\mu\text{m}$  x 980  $\mu\text{m}$  box on each bottom bus bar. The fifth and last lithography layer was for the etch of the pad metallization, and was a 900  $\mu\text{m}$  x 400  $\mu\text{m}$  box at the bottom of



**Figure 1:** The metal layers the students got from the course staff to make the LED. The layers were grown in the MBE, molecular beam epitaxy, machine at NTNU NanoLab. Figure borrowed from the lab manual.

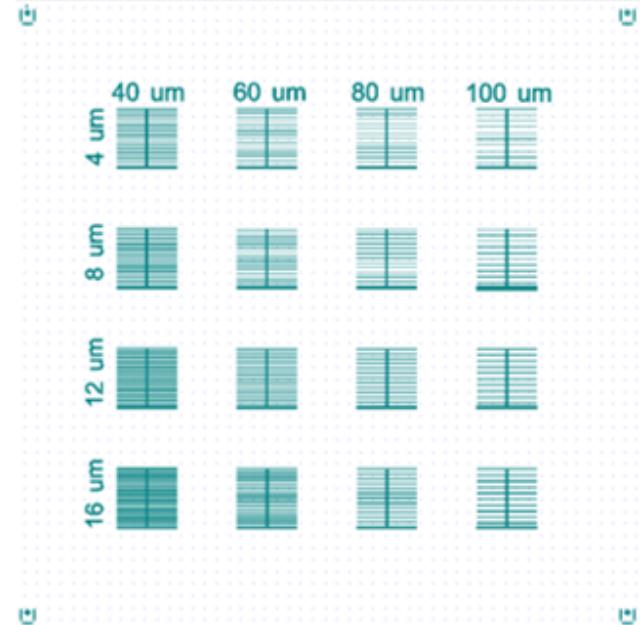
each LED connected to the bottom bus bar. Schematics of the different layers are shown in [Figure 2](#) to [Figure 6](#). Schematics of the alignment marks in layer 1 and layer 2 is shown in [Figure 7](#).

### 3.2. Front contact formation

The bus bar and its fingers were formed with lithography and lift-off. A dose test was done to find the optimal dose and developing time for the resist, ensuring an undercut. To verify this, both a SEM image and optical images of the sample were taken. The optimal dose was 1300 mJ/cm<sup>2</sup> and the optimal developing time was 5 min. All temperatures are probably some degrees off, since the hot plates at NanoLab havt not been calibrated for many years. **FIX THESE NUMBERS** Negative photoresist was used, and the steps were done in the following order:

1. Cleaned the sample with acetone and IPA.
2. Dehydration baked at 150 °C for 5 min.
3. Spin coated MAN 440 resist at 4000 rpm for 30 s with 1000 rpm/s acceleration.
4. Cleaned the backside.
5. Soft baked at 95 °C for 1 min.
6. Exposed the pattern at 1300 mJ/cm<sup>2</sup> in the MLA.
7. Developed in maD-332S developer for 5 min.
8. Optical inspected the pattern.
9. Teaching assistants metallized the pattern with Au.
10. Lift-off with acetone.

Unfortunately, a mix up of the type of developer was done, and the lithography steps had to start over. The optical inspection before round number two showed some bubbles on the wafer, which was probably caused by the



**Figure 2:** Layer 1. Numbers on the top is the width of the fingers in the matrix. Numbers on the left side is the width of the fingers in the matrix. Each LED is 1 mm x 1 mm.

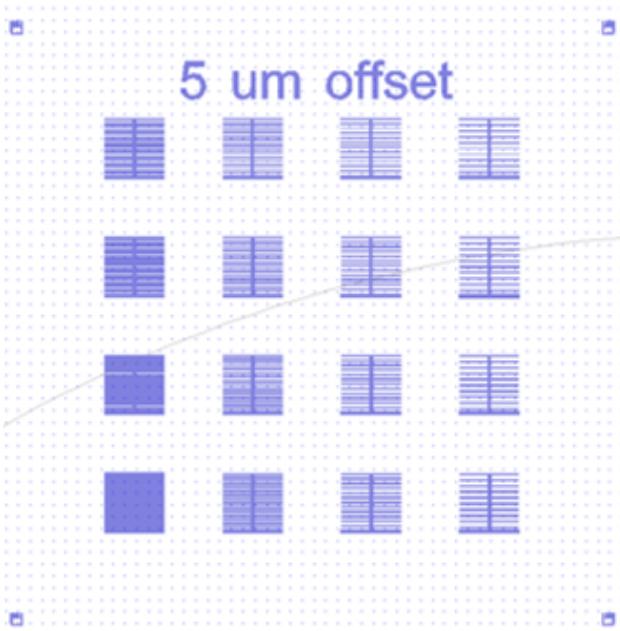
wrong developer. The wafer was cleaned thoroughly with acetone and IPA before the second round, but some residue might have been left behind.

Another problem was that the dose test were done with a resist that got emptied, and a newer resist had to be used for the actual process. When using the new resist the developer time was increased from 5 to 6 minutes, which gave an undercut but damaged the alignment marks and the thinnest fingers.

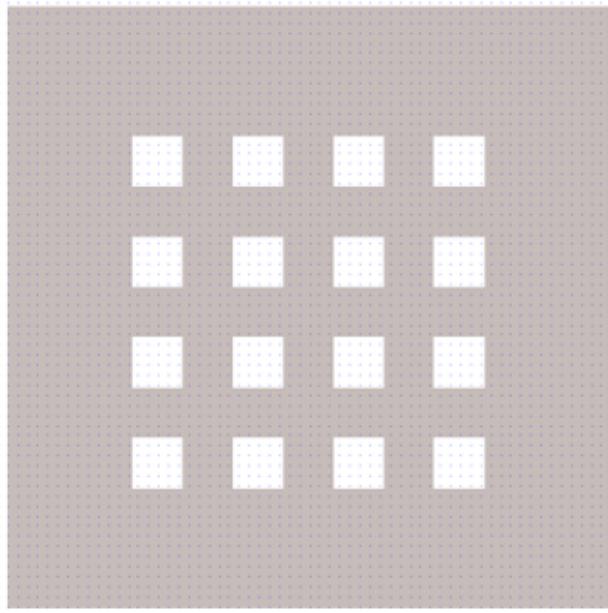
### 3.3. GaAs contact layer etch

The heavy p-doped GaAs layer at the top of the metal stack was etched away to allow light to pass through the LED. The deposited Au fingers were measured to be 250 nm high in the profilometer. Measuring the Au height was important for the later measurement of the etch depth of the 100 nm GaAs layer. The Au fingers were protected with a positive photoresist before the wet etch. Optimal dose for the positive photoresist was found to be 130 mJ/cm<sup>2</sup>. The preperation was done with the following steps:

1. Cleaned the sample with IPA.
2. Dehydration baked at 115 °C for 5 min.
3. Spin coated SPR 700 resist at 4000 rpm for 34 s with 1000 rpm/s acceleration.
4. Soft baked at 95 °C for 1 min.
5. Aligned the pattern in the MLA. The alignment marks were badly damaged, so the alignment was not perfect. See [Figure 17](#).
6. Exposed the pattern at 130 mJ/cm<sup>2</sup> in the MLA.
7. Post exposure baked at 115 °C for 1 min.



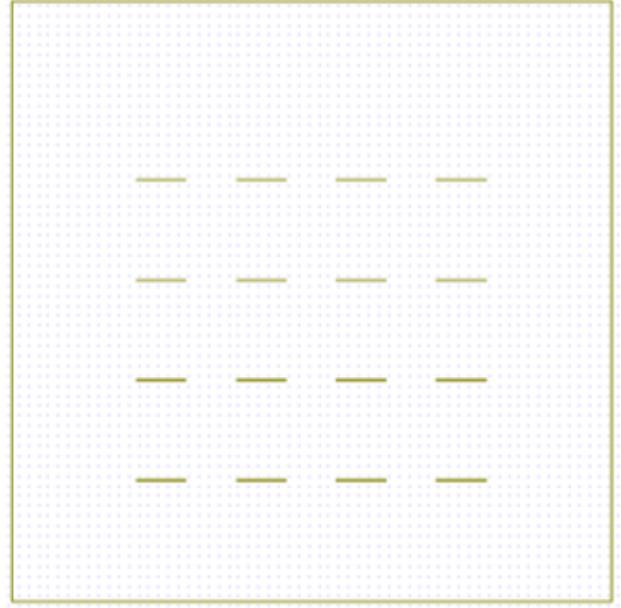
**Figure 3:** Layer 2. This is the same as layer 1, but with a 5  $\mu\text{m}$  buffer on the whole pattern.



**Figure 4:** Layer 3. This is the mesa etch layer. The size of the box covering each LED is 1.012 mm  $\times$  1.012 mm.

8. Developed in maD-332S developer for 30 sec.
9. Optical inspected the pattern to see if it covered the Au fingers.

Quantification of the misalignment with the Verniers were tried, but the Verniers were too badly damaged to get any number out. The wet etch was done at the chemical clanroom at NTNU NanoLab, with NH<sub>3</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O in 3:1:300 ratio. The ammonium hydroxide was 30%. The etch depth was tested on the GaAs dummy sample, and



**Figure 5:** Layer 4. This is the HF etch layer. Each bar is covering a part of the bottom bus bar, with a size of 20  $\mu\text{m}$   $\times$  980  $\mu\text{m}$ .

measured with the profilometer to figure out an etch time which would remove 100 nm of GaAs. The GaAs dummy was etched 50 nm at the first run, thus the time was doubled for the LED etch to achieve 100 nm. The etch steps were as follows:

1. All equipment and chemicals were placed in the fume hood.
2. 3 mL 30% NH<sub>3</sub> was added to the etch tank with 300 ml H<sub>2</sub>O.
3. 1 mL H<sub>2</sub>O<sub>2</sub> was added to the etch tank.
4. The sample was placed in the etch tank for 90 sec.
5. The sample was rinsed with H<sub>2</sub>O and cleaned on the backside.
6. The protective photoresist was removed with acetone and IPA before profilometer measurement.
7. The etch depth was measured with the profilometer.

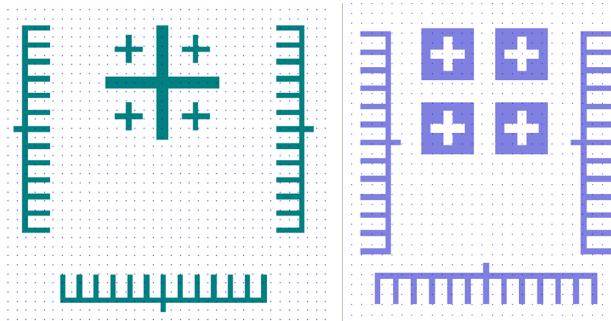
#### 3.4. Backside contact formation

The backside of the LED wafer sample was metallized with Au to form the backside contact. The positive photoresist SPR 700 were chosen, since that one gave better results than MAN 440. The frontside protection was done with the following steps, while the metallization with Au was done by the teaching assistants:

1. Cleaned the sample with acetone and IPA.
2. Dehydration baked at 115 °C for 5 min.
3. Spin coated SPR 700 resist at 4000 rpm for 34 s with 1000 rpm/s acceleration.
4. Soft baked at 95 °C for 1 min.



**Figure 6:** Layer 5. This is the pad metallization layer, where each box is 1 mm x 0.4 mm. The box is covering the bottom bus bar of each LED.

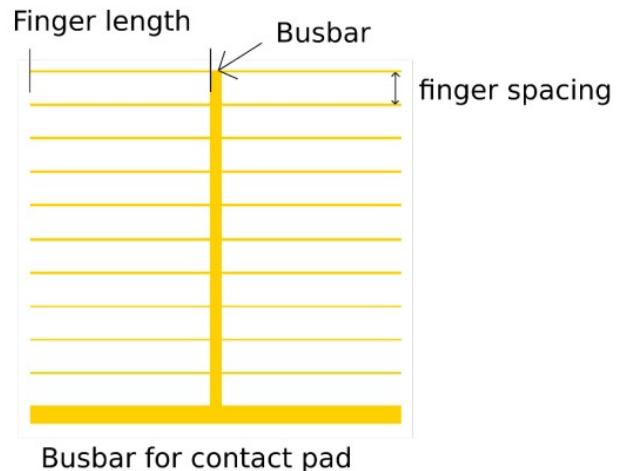


**Figure 7:** Alignment marks for layer 1 and 2. The design allows quantification of the alignment error. These marks are the Verniers design.

5. No exposure was done, since the whole frontside needed to be protected.
6. Post exposure baked at 115 °C for 1 min.
7. Developed in maD-332S developer for 30 sec.
8. Optically inspected the pattern to see if it covered the whole frontside.

### 3.5. Mesa etch, PECVD passivation deposition, and contact annealing

In one session the the mesa was etched, the passivation layer deposited and the contacts annealed. The mesa etch was done with a wet etch with H<sub>3</sub>PO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O 5:5:15, with the goal of separating the 16 LEDs. The mesa etch had to get through the two p-doped Al<sub>0.7</sub>Ga<sub>0.3</sub>As layers, i.e. had to be deeper than 3 μm. The preparation for the mesa etch was to add a positive photoresist mesa mask, which was done in the following steps:



**Figure 8:** Schematic of the LED design. Figure borrowed from the lab manual.

1. Cleaned the sample with acetone and IPA.
2. Dehydration baked at 115 °C for 5 min.
3. Spin coated SPR 700 resist at 4000 rpm for 34 s with 1000 rpm/s acceleration.
4. Soft baked at 95 °C for 1 min.
5. Aligned the pattern in the MLA.
6. Exposed the pattern at 130 mJ/cm<sup>2</sup> in the MLA.
7. Post exposure baked at 115 °C for 1 min.
8. Developed in maD-332S developer for 30 sec.
9. Optically inspected the pattern to see if it covered the LEDs.

The mesa etch and passivation deposition was done in parallel at NTNU NanoLab. The wet etch was first done on the GaAs dummy to test the etch time, where it was found that 1 min 30 sec would be sufficient to etch through the two p-doped layers. The optimal thickness for the passivation layer was 253 nm to minimize reflection. The following steps were done:

1. Deposited Si<sub>3</sub>N<sub>4</sub> passivation layer on Si to find an optimal layer thickness. The recipe used was "(OPT) Si<sub>3</sub>N<sub>4</sub>" for 10 min.
2. Wet etch of the dummy to find a suitable etch time. This etch time was 1 min 15 sec, which was increased by 15 sec for the LED etch.
3. The wet etch was done with H<sub>3</sub>PO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O 5:5:15 mL.
4. The resist was stripped of the dummy, and the etch depth was measured with the profilometer.
5. The inferometer was used to measure the passivation layer deposition thickness.
6. The LED was mesa wet etched as the dummy was, but with 1 min 30 sec etch time.
7. The etch depth was controlled to be deeper than 3 μm in the profilometer.

8. PECVD passivation layer deposition was done on the LED and the dummy with the same recipe as the Si test, because the recipe was found to be good enough. **True????**
9. The last step was the contact annealing, which was done with warm up to 420 °C, and 30 sec annealing at 420 °C, before cooling down to room temperature.

### 3.6. Planarization and passivation layer etch

The planarization and lithography preparation for HF etch was done. The passivation layer HF etch was done by the teaching assistants. The planarization and preparation for the passivation layer etch was to add a thick positive photoresist with a mask opening on the bottom bus bar, and was done in the following steps:

1. Cleaned the sample with acetone and IPA.
2. Dehydration baked at 150 °C for 5 min.
3. Spin coated AZ5214E positive resist at 1000 rpm for 34 sec with 250 rpm/s acceleration.
4. Soft baked at 95 °C for 1 min.
5. Exposed the pattern at 80 mJ/cm<sup>2</sup> in the MLA.
6. Developed in 70:30 ma-D 332S:H<sub>2</sub>O developer for 1 min 30 sec.
7. Hard baked at 175 °C for 15 min.
8. Optical inspection of the pattern.
9. Teaching assistants performed HF etch to expose the Au in the bottom bus bar.

### 3.7. Pad metallization

Lithography on the LED sample was done to prepare for the pad metallization. The teaching assistants did the pad metallization. The preparation was to make a negative photoresist mask for the pad metallization, and was done in the following steps:

1. Cleaned the sample with IPA.
2. Dehydration baked at 115 °C for 5 min.
3. Spin coated MAN 440 resist at 4000 rpm for 30 s with 1000 rpm/s acceleration.
4. Soft baked at 95 °C for 1 min.
5. Exposed the pattern at 1300 mJ/cm<sup>2</sup> in the MLA
6. Developed in maD-332S developer for 5 min.
7. Optical inspected the pattern to see if the pattern covered the bottom bus bar and an area below.
8. Handed in the sample to the teaching assistants, who did the pad metallization with Au.
9. Lift-off was done with acetone.

### 3.8. LED testing/characterization

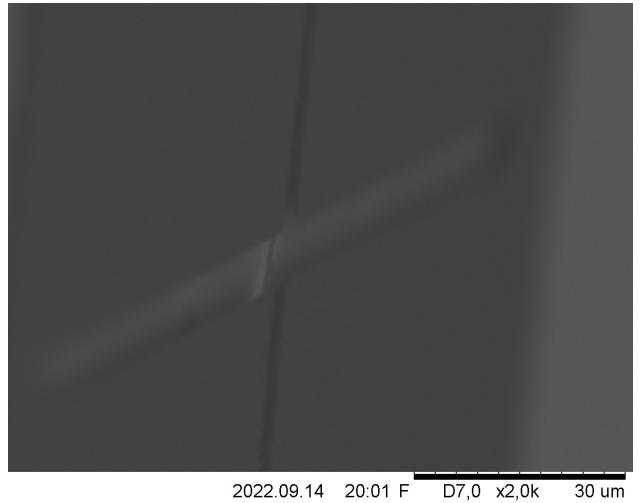
After all these steps the LED was ready for testing. Testing was done at IES, with ...

## 4. Results

### 4.1. Photoresist Profile

**Figure 9** shows an SEM image of the photoresist profile of the dose test sample where undercut was most visible. This is the sample with a dose of 1300 mJ/cm<sup>2</sup> and 5 minutes developing time. The depth of the undercut, i.e. the difference between the top and bottom of the profile, is estimated to be roughly 1 µm.

**Figure 10a** and **Figure 10b** show 100X magnification images of one LED where the focus is on the bottom and the top of the profile, respectively. This shows that the bottom area of the finger is smaller than the top area, again verifying that an undercut profile is obtained with a dose of 1300 mJ/cm<sup>2</sup> and 5 minutes developing time.



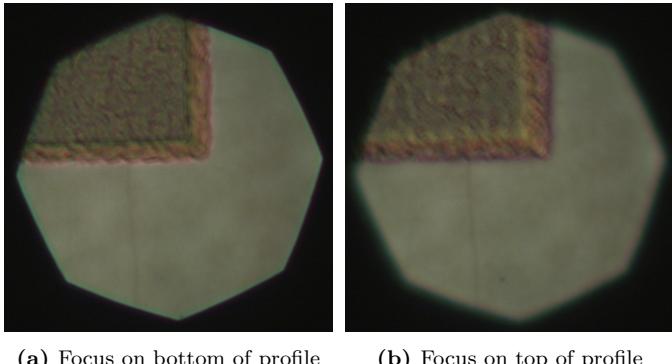
2022.09.14 20:01 F D7,0 x2,0k 30 um

**Figure 9:** Secondary Electrons (SE) SEM image of the photoresist profile in the dose test sample where the best undercut profile was achieved. The optimal dose was 1300 mJ/cm<sup>2</sup> and the optimal developing time was 5 minutes. The exact undercut is not measured, but it is estimated to be around 1 µm. Acceleration voltage in the SE image was 5 kV. SEM image taken at the Hitachi TM3000 table top SEM at NTNU NanoLab.

### 4.2. Etching

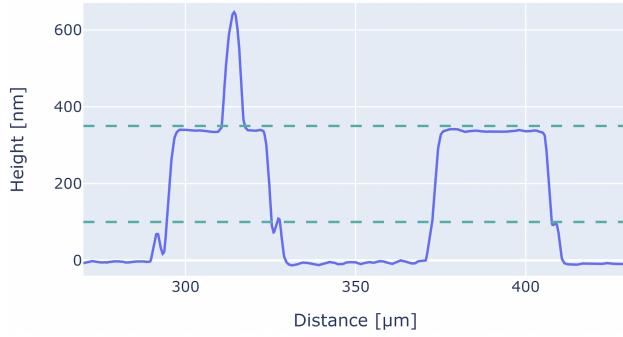
The GaAs wet etch of the dummy was done for 45 seconds and gave a depth of 50 nm, thus the etching of the LED was done for twice as long at 90 seconds and gave a depth of 100 nm. This is an etch rate of 1.11 nm/s. The measured height of two fingers using the profilometer is shown in **Figure 11**. The other measurements of the fingers gave similar results. Before the etch the Au fingers were measured to be 250 nm high. In the figure it is possible to see the etch edge, which is marked with the green line at 100 nm. The second green line is at 350 nm, which is the height of the finger after the etch. A profilometer artifact is shown in **Figure 12**.

The deep AlGaAs wet etch for the mesas was done for 1 minute and 15 seconds on the dummy which gave 3000



(a) Focus on bottom of profile      (b) Focus on top of profile

**Figure 10:** 100X magnification optical images of one finger on one LED. This illustrates that the photoresist profile is undercut.



**Figure 11:** Profilometer data plot of the GaAs top layer etch. The etch was 100 nm deep, which is sufficient to get through the light absorbing layer. The plot shows an artifact on top of the finger to the left, but these were not examined further.

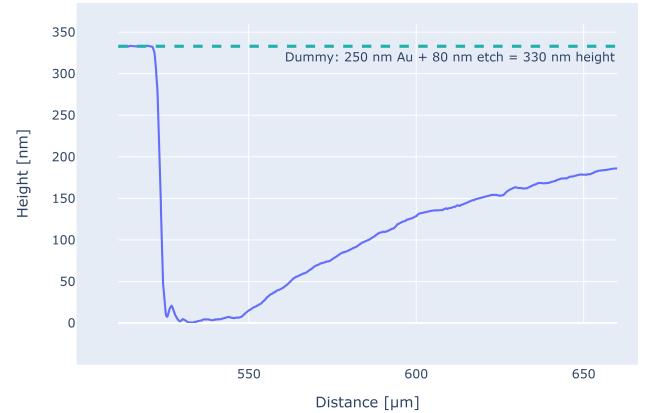
- 3400 nm of etch depth, and thus the time was increased to 1 minute and 30 seconds for the LED, which gave 3100 - 3500 nm of etch depth. The deviation in etch depth is illustrated in [Figure 13](#), where the deviation is due to the fact that the profilometer data is not flat before and after the mesas. The etch rate was around 40 nm/s.

#### 4.3. PECVD

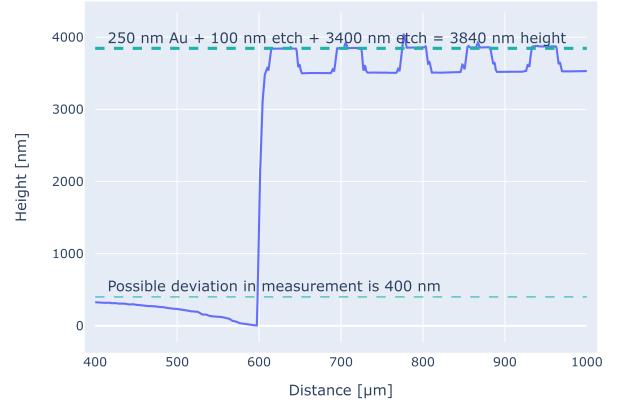
The result of the PECVD of  $\text{Si}_3\text{N}_4$  was inspected using an ellipsometer. From this, the reflectance as a function of wavelength was obtained, as can be seen in [Figure 14](#). The goodness of fit was 0.9926. The lowest measured reflectance was 0.29 % at 667.7 nm. At a wavelength of 675 nm, the reflectance was 0.42 %. From the ellipsometer, the thickness of the  $\text{Si}_3\text{N}_4$  layer was measured to be 249.70 nm. From [Equation 1](#), with a refractive index  $n$  of 2.02 at  $\lambda \approx 670$  nm [1], the thickness is calculated to be 247.91 nm. These results are summarized in [Table 1](#).

#### 4.4. Optical Characterization of PECVD

After the PECVD and its finishing steps, an 10X optical image was taken of the LED. This image can be seen in [Figure 15](#). From this, it can clearly be seen that the



**Figure 12:** Profilometer data plot of GaAs dummy on the etch edge. The etch depth here was 80 nm, which was deeper than around the fingers. However, this plot shows an artifact in the profilometer, which is the curve starting at around 550  $\mu\text{m}$ . The upwards curve continues upwards outside the plot till 350 nm, which is higher than the finger height.



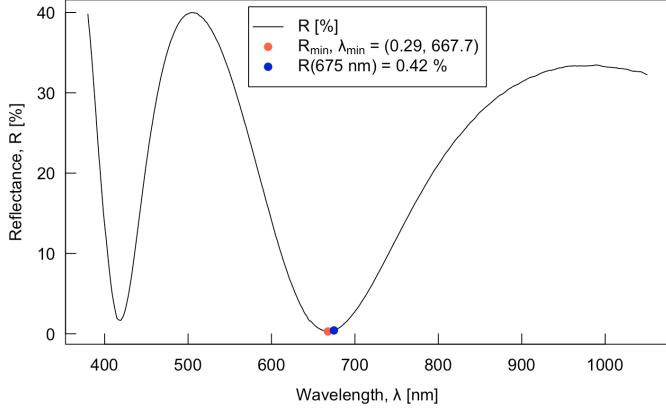
**Figure 13:** Profilometer data plot after the mesa etch of the LED sample. The etch is 3500 nm deep at the edges of the mesas, but the profile is not flat before and after each mesa. The data points outside the mesas flattened at 400 nm, which puts the etch depth between 3100 and 3500 nm. The height of the fingers are around 3840 nm, because of the GaAs layer and Au fingers on top of the AlGaAs.

$\text{Si}_3\text{N}_4$  film is not uniform. Visually, it seems that the film has cracked and that there are some impurities present.

#### 4.5. Final Optical Inspection

Using an optical microscope, the final LED sample was inspected. [Figure 16a](#) shows the visually best LED, which has an 80  $\mu\text{m}$  period and a 4  $\mu\text{m}$  finger width. [Figure 16b](#) shows the visually worst LED, which has a 40  $\mu\text{m}$  period and a 16  $\mu\text{m}$  finger width.

A final 50X magnification optical image were taken of all four alignment marks. The result can be seen in [Figure 17](#). From these pictures, it is not possible to give a numerical estimate on the alignment accuracy



**Figure 14:** Reflectance as a function of wavelength for the PECVD  $\text{Si}_3\text{N}_4$  film.

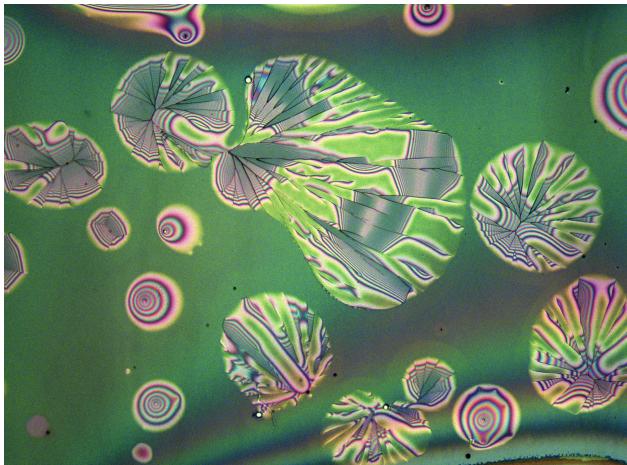


(a) Visually best LED. 80  $\mu\text{m}$  period and 4  $\mu\text{m}$  width.  
(b) Visually worst LED. 40  $\mu\text{m}$  period and 16  $\mu\text{m}$  width.

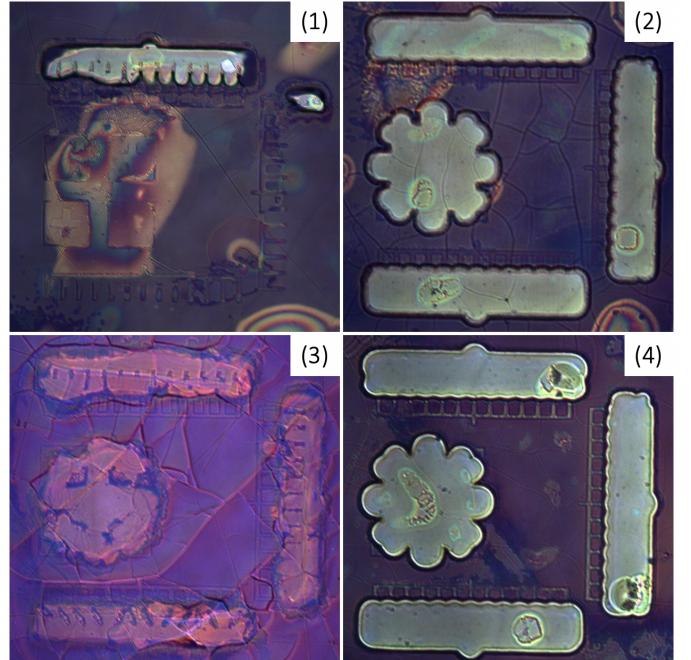
**Figure 16:** 5X magnification optical images of the visually best and worst LEDs.

**Table 1:** Key parameters for the PECVD  $\text{Si}_3\text{N}_4$  film obtained from the ellipsometer.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Lowest reflectance               | 0.29 %    |
| Wavelength at lowest reflectance | 667.7 nm  |
| Reflectance at 675 nm            | 0.42 %    |
| Measured thickness               | 249.70 nm |
| Calculated thickness             | 247.91 nm |



**Figure 15:** Optical image of the LED.



**Figure 17:** 50X magnification optical images of the four alignment marks.

## 5. Discussion

### 5.1. Photolithography

All the lithography processes used in this work gave valuable experience. One of the experiences was how to do a dose test to get a sufficient undercut while using negative photoresist. The lab manual for the course [2] states that the undercut should be at least 1  $\mu\text{m}$  deep, while the teaching assistant stated that 0.5-1  $\mu\text{m}$  would be sufficient. Getting an exact measurement of the undercut was difficult with the Table Top SEM, because the tilting and rotation of the sample in the chamber is very restricted. Quantification of the undercut with the Table Top SEM, but the undercut is clearly visible in the SEM image in Figure 9. Estimating the undercut was easier when using the optical microscope. First it was assessed whether the slope visible in the optical images in Figure 10b and Figure 10a was an undercut or not. Over- and under focusing on the edge indicated that the slope was an undercut, and this was confirmed in the SEM. The quantification of the undercut was done by measuring the length of the slope and comparing this to the width of the finger. This is a crude approximation, but it confirmed that the undercut was in the range of 0.5-1.5  $\mu\text{m}$ , assuming that the widest part of the finger was 5  $\mu\text{m}$  wide.

If all the photolithography steps were done again from start, positive photoresist would have been preferred over negative photoresist to get the best possible results. All the steps with positive photoresist gave better results than with negative photoresist. One example of the bad xxxxx Negative photoresist is supposed to be better to use for lift-off, because of the undercut, but it was concluded that the positive resist gave sufficiently good results and less edge problems when used in the lift-off process. One of the students did use positive photoresist for the lift-off process in his project thesis, and found there too that the positive resist gave good enough results.

### 5.2. Etch

The plots from the profilometer on the etches show that the etch is not perfectly flat. Three artifacts have been identified in the etch process, which are the cause of the non-flat etch.

One artifact is the contact loss shown in Figure 12. Here the depth is measured to 80 nm, but this is uncertain since the contact is lost. The contact loss can be countered with the right settings on the profilometer. The artifact could have been something else, but the contact loss is the most likely cause since the profilometer data outside the plot on the left side is flat and correct.

A second artifact are on the vertical edges, where the etch is varying a lot. This is illustrated in Figure 11. The other vertical edges varied in other but similar ways. This could both be caused by the etch process and the profilometer. The profilometer might struggle to measure around vertical edges. The etch process could be affected

by the increased area and by different etch rates on different crystallographic planes.

A third artifact is the squiggly surface, shown between the fingers in Figure 11. This artifact is caused by the etch process, and is present all over the wafer where the etch was done. The surface is varying around  $\pm 5 \text{ nm}$ , which is a lot for a 100 nm etch. This artifact could potentially block some of the light from the LED, but it is not clear how much of the light this could block.

### 5.3. Deposition of Passivation Layer

If all process steps are done correctly, the LED will emit light at 675 nm. For  $\text{Si}_3\text{N}_4$ , this corresponds to an optical thickness of around 250 nm. The optical thickness of  $\text{Si}_3\text{N}_4$  was measured to be 249.70 nm and calculated to be 247.91 nm. This is very close to the target, which is good. It is also expected that the values are close.

In order to adjust the thickness to get even closer to the target thickness, the deposition time could be adjusted. The deposition time was 18 minutes and 35 seconds. This corresponds to a deposition rate of 0.22 nm/sec, assuming that the deposition was linear and that the measured thickness is correct. Using these numbers, the deposition time could be adjusted to 18 minutes and 36 seconds, which would give an optical thickness of 249.9 nm, slightly closer to target value.

### 5.4. Surface artifact

The surface of the LED was far from perfect throughout the process. While alignment in the MLA was done, multiple surface impurities were visible. These impurities are probably what is seen as a high and abrupt peak in the profilometer data in Figure 11 around 320  $\mu\text{m}$ . Peaks like this one are visible in all the profilometer data from the sample. The optical microscope images in Figure 15 show that the surface have many surface impurities which have cracked before, during or after annealing.

The annealing process made the surface artifacts and more visible. It is most likely that the surface impurities were present before the etch, and that the etch process has made the area around the impurities more susceptible to cracking and slightly different etch rates. The different etch rates are visible as different colors in the optical microscope images in Figure 15, which can arise due to different thicknesses. Another argument for the artifacts being a result of the etch process and not the annealing, is that the passivation layer totally covers the surface and protects it from damage.

## 6. Conclusion

## References

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