Fabrication of Light Emitting Diode

2.676 2.675 Lab 10

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Background

LEDs are widely used for illumination and display applications. There are many types of LEDs depending on how they generate different colors. One type uses a single-color panel as the source of the light and modulates it with different approaches. For example, LCD uses liquid crystal to rotate polarized light. Liquid crystals can be controlled electronically. Quantum-LED also works in a similar way, using quantum dots to modulate the backlight. Another type of LED uses self-emitting pixels as the source of the light. For example, OLED uses organic compounds as the material for the pixels, and micro-LED uses compound semiconductor materials as the self-emitting materials. Among these LEDs, micro-LED has the highest efficiency, highest lifespan, and highest brightness and contrast. Therefore, it's considered as the most promising type of LED for the future.

Electrons and holes are deliberately introduced to the film by the doping process, which creates the diode structure. In an LED, one layer will have excess electrons, while the next layer will have excess holes (deficit electrons). When this diode structure is placed under an electric field, the electron gradient can generate an electron flow in the structure, thereby generating light. For a semiconducting material, each band with one specific energy can only hold a limited number of electrons. All electrons need to fill in bands with increasing energy until all the electrons are filled. The filled band with the highest energy is called valence band. The unfilled band with lowest energy is called conduction band. The energy gap between the valence band and the conduction band is called the band gap. The band gap is a material property and is independent of the doping level. When an electric field is applied, electrons in the valence band are excited to the conduction band and then recombined back to the valence band. The energy is released in the form of photons during the recombination process. Therefore, the energy of the light, which determines the wavelength, equals the band gap energy of the material. InGaN is the most common material for blue and green LEDs and AlGaInP is the most common material for yellow and red LEDs. By changing the elements' composition in one compound semiconductor, the wavelength can also be modulated in a small range.

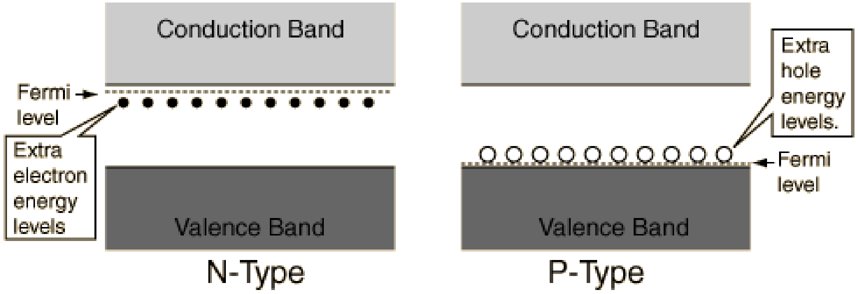


Figure 1: n-type and p-type semiconductor

http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/dsem.html

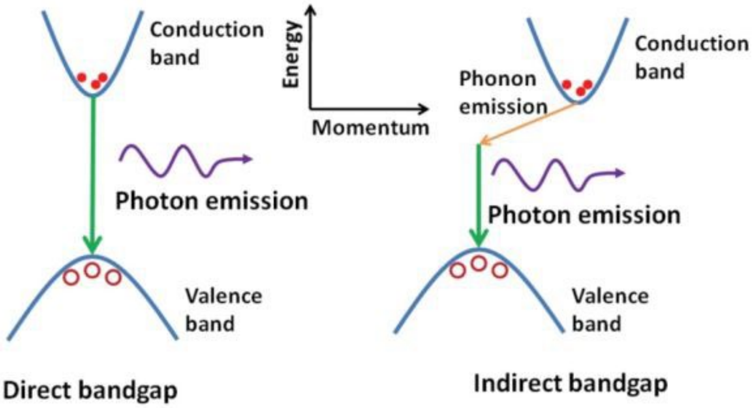


Figure 2: Direct and indirect bandgap

Thurston, Cameron Robert, "Band Gap Engineering Of Titania Systems Purposed For Photocatalytic Activity" (2017). Electronic Theses and Dissertations. 1071.

Spin coating:

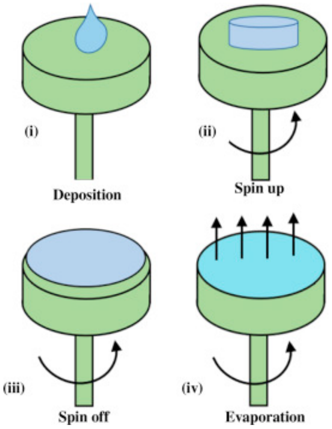


Figure 3: Spin coating process

Spin coating is a process of depositing a uniform layer of thin film onto a wafer. It's the major technique used for applying photoresist on the sample. First, the sample is mounted at the center of the spin coater, usually held by vacuum. A small amount of liquid photoresist is dropped at the center of the sample. The liquid will spread to cover the whole wafer under the centrifugal force when the spinner starts to spin. The spin speed ranges from 1000rpm to 10,000rpm. The thickness of the film depends on the **viscosity of the coating material** and the **spin speed**. Lower viscosity and higher spin speed result in thinner film. The target thickness of the photoresist should be determined by the post etching process. The spin coating material is usually dissolved in solvent, which is volatile. The evaporation during spin coating and post baking will dry the solvent and leave only solid material on the surface. There are also two types of photoresists: positive photoresist and negative photoresist. For positive photoresist, the exposed area in the photolithography process is soluble in the developer. For negative photoresist, the unexposed area is soluble in the developer.

Knowledge Check 1:
What is the type of the photoresist (positive or negative) do we use in our process? If we decide to use the other type, what necessary change(s) do we need to make?

Photolithography:

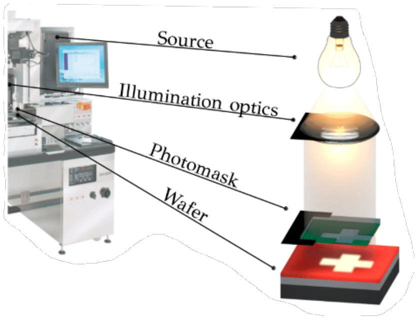


Figure 4: mask aligner

Vetter, Andreas. (2019). Resolution enhancement in mask aligner photolithography. 10.5445/IR/1000104490.

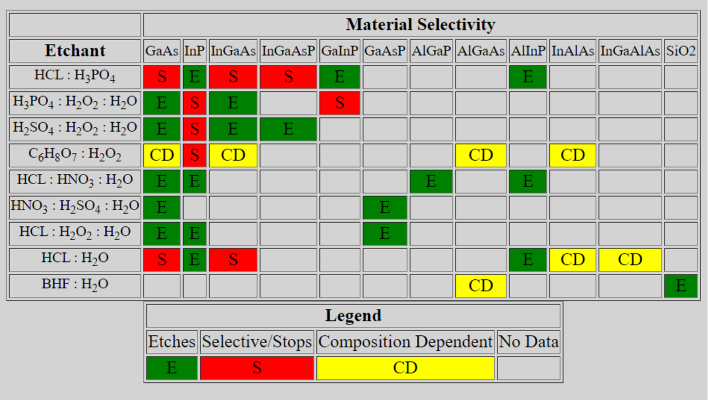
Figure 5: Heidelberg MLA-150 maskless aligner

A typical lithography process uses mask aligner to expose the pattern on the photoresist. Depending on the property of the photoresist (positive or negative), the exposed pattern will be kept or removed from the substrate. Before the lithography, a glass mask needs to be made with shaded and clear area defining the target pattern. A mask aligner consists of a UV light source and multiple lenses. Lenses generate a uniform illumination from the UV light source. The glass mask is placed under the illumination and the substrate with the photoresist is placed at the bottom. The illumination only goes through the clear area of the mask to partially expose the photoresist on the mask. Masks with different patterns are used to fabricate multilayer devices. Markers (usually cross or square) at four corners are needed to align different layers to correct positions. In this week’s lab, we will use the Heidelberg MLA-150 Maskless Aligner. It utilizes a diode laser to directly pattern the photoresist without a physical mask, providing a high flexibility compared with traditional mask aligner. However, as laser only exposes a small point, the process time can be substantially longer for large wafers compared with the mask aligner.

Etching Process:

After the chemical developing process, photoresist only covers and protects the patterned area, while the rest of the area will be etched to a target depth with the etching technique. There are different types of etching techniques. Factors such as pattern sizes, applications and safety issues need to be considered when choosing the process. Most etching techniques fall into two categories: wet etching and dry etching.

Wet etching relies on liquid solutions with corrosive properties. Etchants can have chemical reactions with specific materials to remove them. By choosing etchant wisely, wet etchant can only etch one layer while stopping at next. In this way, wet etching has better selectivity over dry etching.



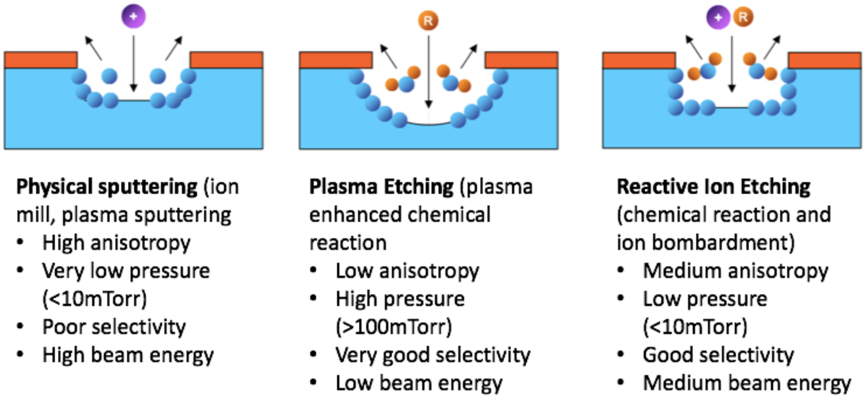
	Material Selectivity											
Etchant	GaAs	InP	InGaAs	InGaAsP	GaInP	GaAsP	AlGaP	AlGaAs	AlInP	InAlAs	InGaAlAs	SiO2
HCL : H_3PO_4	S	E	S	S	E				E			
H_3PO_4 : H_2O_2 : H_2O	E	S	E		S							
H_2SO_4 : H_2O_2 : H_2O	E	S	E	E								
$C_6H_8O_7$: H_2O_2	CD	S	CD					CD		CD		
HCL : HNO_3 : H_2O	E	E					E		E			
HNO_3 : H_2SO_4 : H_2O	E					E						
HCL : H_2O_2 : H_2O	E	E				E						
HCL : H_2O	S	E	S						E	CD	CD	
BHF : H_2O								CD				E

Legend			
Etches	Selective/Stops	Composition Dependent	No Data
E	S	CD	

Figure 6: Etchant selectivity for III-V material

https://terpconnect.umd.edu/~browns/wetetch.html

Dry etching relies on high-energy particles to physically knock off atoms of the materials. Since high-energy particles etch all materials with low selectivity, the thickness of the photoresist needs to be better controlled as it will be removed during the etching process as well. The directional beam of the dry etching can make it an anisotropic process. This allows it to fabricate much smaller features compared with wet etching.



Physical sputtering (ion mill, plasma sputtering
- High anisotropy
- Very low pressure (<10mTorr)
- Poor selectivity
- High beam energy

Plasma Etching (plasma enhanced chemical reaction
- Low anisotropy
- High pressure (>100mTorr)
- Very good selectivity
- Low beam energy

Reactive Ion Etching (chemical reaction and ion bombardment)
- Medium anisotropy
- Low pressure (<10mTorr)
- Good selectivity
- Medium beam energy

Figure 7: Different types of dry etching

https://materean.com/dry-etching/

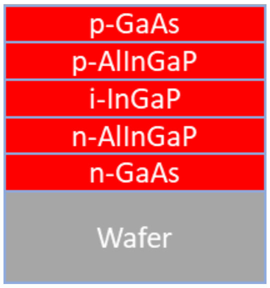
Knowledge Check 2:
What are the merits of wet etching and dry etching? (list at least two for each) What necessary changes do we need to make if we change to use dry etching for our process?

Process of LED fabrication:

- **<u>Structure growth:</u>**

1. Semiconductor wafer is made based on the color of the LED being fabricated. For the next epitaxial steps, these substrate wafers need to have similar lattice constant compared with the target LED materials. For example, GaN and sapphire are always used as the substrate for InGaN and GaAs are always used as the substrate for AlGaInP. These substrate wafers are usually manufactured in high pressure and high temperature chambers and then sliced into thin wafers. Before the next step, these wafers are cleaned by ultrasonic and chemical methods to remove dirt and organic contaminants on the surface.

2. Diode structures are grown on the substrate wafer by various thin film deposition methods. Metal-Organic Chemical Vapor Deposition (MOCVD) is one of the most widely used epitaxial processes to fabricate LED. First a layer of n-type doping InGaN or AlGaInP are deposited in the MOCVD chamber. For InGaN, Trimethyl-gallium/triethyl-gallium, trimethyl-indium, and ammonia will serve as precursors for Ga, In, and N. Silane is used as the source of Si for n-doping active layer. For AlGaInP, Trimethyl-gallium, trimethyl-aluminium, trimethyl-indium will serve as precursors for Ga, Al, In and P, respectively. Disilane will serve as the Si precursor of n-doping active layer.
3. Quantum well layers are grown on the top of the n-doping layer to enhance the efficiency of the LED. Quantum well is heterostructure of alternating thin layers of material with different band gaps. The special structure of the quantum well allows it to capture electrons and holes efficiently. This 2D carrier confinement can greatly enhance the efficiency of the LED. InGaN/GaN quantum well is widely used in InGaN LED fabrication and AlGaInP/InGaP quantum well with different element composition is widely used in AlGaInP LED.

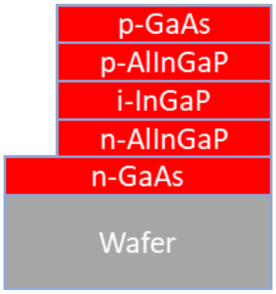


4. P-doping layer of the diode will be deposited on the top of the quantum well. Bis(cyclopentadienyl)magnesium will serve as the precursor of Mg for InGaN p-doping active layer. Dimethyl-zinc will serve as the precursor of Zn for AlGaInP p-doping active layer.

Knowledge Check 3:
Describe the function of each layer in the LED structure.

- **Mesa structure fabrication:**

1. CAD drawing is made by *AutoCAD 2025*. The size of one single pixel is defined as 500µm × 500µm.
2. Spin coat photoresist: AZ3312 at 3000rpm for 45s to obtain a uniform thin layer. Bake the sample at 100℃ for 90s to evaporate the solvent in the photoresist.
3. Import the CAD drawing file into the DirectWrite-MLA maskless aligner. Expose the pattern with laser. Since AZ3312 is a positive photoresist, the exposed part will be soluble to the developer.
4. Develop the UV exposed area using AZ726 MIF (metal ion free) developer for 60s to remove exposed photoresist.
5. Wet etch GaAs with Chromium Etchant and (Al)InGaP with HCl/H_3PO_4 (1:1). Since HCl/H_3PO_4 (1:1) selectively etches (Al)InGaP. The etching process will stop at the n-GaAs layer.
6. Erase photoresist using acetone (with swab, if needed)

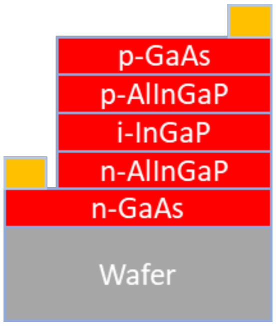


Knowledge Check 4:
Sketch a picture of an actual LED single pixel. How does the size of the pixel compare with the defined size in the mask? How can we change our process to make the actual size more accurate?

- **Metal lift-off process: (This lab)**

Metal contact is used to connect the device to the power supplier. Contact metals need to have small contact resistance and good adhesion on the substrate material.

1. Spin coat PMGI-5 at 3000rpm for 30s. Bake at 175℃ for 4min. PMGI-5 forms a layer to generate undercut. Spin coat photoresist AZ3312 at 3000rpm for 45s. Bake at 100℃ for 90s. **Tool: Spinner-DualResist-U12, Hotplate-Tower-U12.**



2. Import the CAD drawing file into the DirectWrite-MLA maskless aligner. Choose the second layer (metal contact). Expose the pattern with laser. **Tool: DirectWrite-MLA150-AirAF.**
3. Develop the UV exposed area using AZ726 mif developer for 60s to remove exposed photoresist. **Tool: Develop-L08.**
4. Deposit Ti/Au (10nm/100nm) using Ebeam deposition. **Tool: EBEAM-Temescal-LL.**
5. Heat N-methyl-2-pyrrolidone (NMP) to 70°C and submerge sample inside for 2 hours to move metal/photoresist. Sonication may be required to promote this process. **Tool: Liftoff-L08.**
6. Rinse the sample with acetone/IPA. **Tool: Liftoff-L08.**

Knowledge Check 5:
Why do we need metal contact for semiconductor devices? What are the functions of Ti and Au for our device?