

UNIVERSITY OF
WATERLOO



FACULTY OF ENGINEERING
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UNIVERSITY OF WATERLOO

ELECTRICAL & COMPUTER ENGINEERING
ECE 499 ENGINEERING PROJECT

**Advanced Packaging for μ LEDs using Indium
Electroplating**
In Fulfillment of ECE 499 Course Requirement

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Abstract

Micro LEDs (μ LEDs) are an exciting, new technology that hold the potential to improve upon the capabilities of the incumbent display technologies of liquid crystal displays (LCDs) and organic light emitting diodes (OLEDs). Researchers and industry leaders deem μ LEDs capable of significant advantages in display technologies particularly with key performance metrics in contrast, colour gamut, pixel response timings, display lifetime, and power consumption. Currently there are a variety of technical challenges in fabrication to making the dream of μ LED displays a reality. During this research project I aim to assist in developing a process for packaging μ LED displays onto an addressable backplane. To achieve this we use electroplated indium to create a mechanical and electrical connection between the μ LEDs and thin-film-transistor (TFT) backplane.

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Symbol	Definition	Unit
A	Area	[mm ²]
I	Current	[A]
J	Current Density	[mA/mm ²]
V	Voltage	[mV]
R	Resistance	[Ω]

Table 1: Nomenclature Table

1 Introduction

LEDs are exceptionally efficient when compared to legacy lighting technologies like arc, incandescent, fluorescent lighting, and others. The advantages inherent to the technology have allowed LEDs to enter a variety of light applications like automotive, general lighting, and display backlighting and many other use-cases. [1] Conventional inorganic LEDs have MESA dimensions generally greater than $(300 \times 300)\mu\text{m}^2$, however μ LEDs target an area below $(100 \times 100)\mu\text{m}^2$ to $1\mu\text{m}^2$ [2]

One of the earliest claims to the discoveries of the LED was by Oleg Losev in the 1920s, the work was generally ignored and the conjectured theory for the operation was incorrect, the subsequent research also focused on SiC and II-IV semiconductors. This era of research was generally impractical and did not produce sufficient light. However, with the arrival of III-V semiconductors like GaAs, GaSb, InP, and SiGe there was significant progress in luminosity, although sadly this was all within the infrared spectrum. Visible LEDs would emerge as research in the area quickened, the technology was based on GaAsP epitaxy over GaAs substrates. This would bring forth the advent of commercializable LEDs that would now be seen everywhere. Eventually efficiency and luminosity would surpass that of traditional lighting solutions like filament based tungsten and bring us to where we are today with LEDs being used in nearly all lighting and display applications.

1.1 Motivation for μ LEDs as a Technology

LCDs and OLEDs currently dominate the display market, each technology comes with its trade-offs and current innovations with quantum dots and fully addressable back-lit mini-LED panels aim to address some shortcomings concerning contrast, colour accuracy, power consumption, brightness, lifetime, and response times.

μ LEDs aim to address many of these concerns as well, by offering a number of advantages over traditional LCD and OLED displays. The biggest advantage μ LEDs would provide over LCDs is the power efficiency where LCDs suffer from high power loss due to the multiple diffuser and filtering layers required to compose a screen (CITE AND REWORD). A commonly cited number is that LCDs loose nearly 70-90% of the flux introduced by the backlight to the various polarizing layers that comprise the display. In contrast, as μ LED displays would be entirely emissive, none of the light would be lost to the conventional filtering layers. (IS THIS EVEN TRUE, IS LIGHT LOST TO PHOSPHOR LAYERS?)

1.2 Hurdles in μ LED Technology

IDENTIFY COMMON HURDLES IN MICRO LED TECHNOLOGY

SHOW WHICH OF THESE PROBLEMS WE ARE AIMING TO FIX OR SOLVE FOR

1.3 Motivation for Indium as a Diebonding Material

EASE OF INDIUM AS AN ELECTROPLATING MATERIAL

LOW MELTING POINT

SOFTNESS OF MATERIAL/DUCTILITY

LOW likelihood OF SURFACE OXIDES

EASE OF WETTING TO SURFACE

2 Indium Electroplating

2.1 Introduction

There are a variety of methods for indium electroplating, while I did not select the electroplating process there are a variety of methods available that are commonly used in industry. The largest differences tend to be in what comprises the solution and the operating temperatures.

2.2 Process

The indium electroplating process is based on a now industry standard process that is known to yield good results while requiring a minimum of process optimization. Indium easily allows for wafer bumping where the deformability, low melting point, and cold welding properties [3]. While other alloys consisting of tin and lead or tin, silver, and copper are also used for these processes they come with other disadvantages such as large crystal sizes and high sensitivity to temperature. The plating solution provided by Indium corporation contains

Adapting the indium electroplating process to the E3-3139 and the resources available there, the process is in Appendix A.

The process used there allows us to electroplate indium onto the substrate that is Chrome-Gold on Sapphire. Gold is an excellent material for indium to easily electroplate onto, and is particularly effective for eutectic bonding for In – Au as the alloy that is formed is able to effectively join the wafers [4].

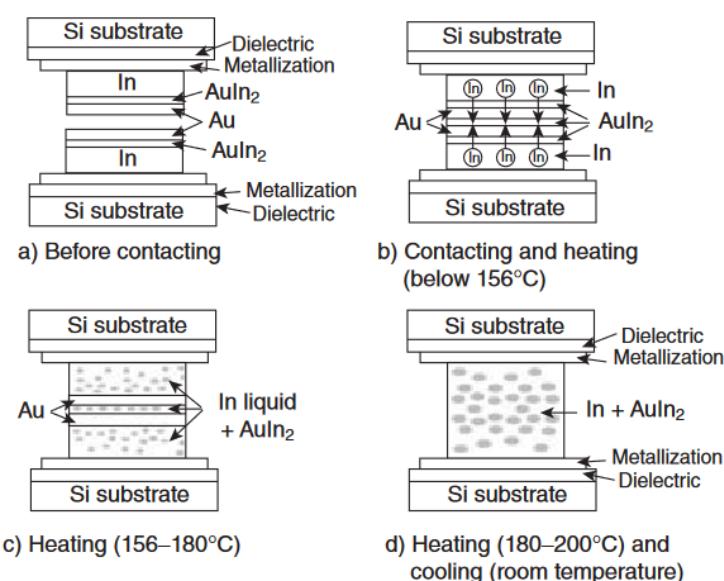


Figure 8.6 Bonding principle of In–Au microbumps.

Figure 1: Eutectic bonding of In – Au micro-bumps

2.3 Existing Setup Description

In summary the process has us prepare the sample with acids before placing into the plating solution. Then the sample holder and sample are submerged in the plating solution and the current source is applied. However, due to cost constraints a voltage source was obtained to perform in place of a current source.



Figure 2: Image of the flat mouth alligator clip used to clamp onto the sample

A current source would have been preferred over a voltage source due to several reasons. Since electroplating is a process where metal ions are deposited on a substrate through the use of an electric current. The amount of metal deposited is directly proportional to the amount of electric charge that flows through the system, which means that controlling the current is crucial for controlling the thickness and quality of the plated layer.

With a current source, the current can be precisely controlled and maintained at a constant level, which results in consistent and uniform plating as a function of time. On the other hand, a voltage source may not provide a consistent current, as the resistance of the plating solution can vary due to factors such as temperature or impurities, leading to poor plating results.

Another advantage of using a current source is that it allows for better control over the plating process and reduces the risk of over-plating or under-plating. With a voltage source, the voltage applied to the system can cause the plating rate to fluctuate, which can result in uneven thickness or even damage to the substrate. In contrast, a current source ensures a constant and controlled deposition rate, which minimizes the risk of defects or damage to the substrate.

Using a voltage source with an ammeter can be equivalent to a current source in certain situations. This is because the voltage applied to a circuit is directly proportional to the current flowing through it. By measuring the current in the circuit using an ammeter, the current can be controlled by adjusting the voltage. In this way, the voltage source with an ammeter can effectively act as a current source.

The sample holder consists of two plastic blocks that are held together by two steel bars. Thumbscrews are used to lock the relative position of the plastic pieces in place while the assembly 'floats' on the lip of the beaker the sample is submerged into. One of the two plastic pieces has a stopper that helps constrain the position of the assembly on the beaker while the other plastic piece holds the glass rod and alligator clip.

The glass rod is attached to the plastic piece and has the alligator clip on it. The clip and corresponding cathode holder are wrapped in a PTFE sleeve that helps minimize stray electric fields and electroplating onto the cathode wire.

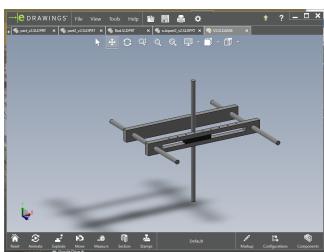


Figure 4: 3D Rendering of the sample holder

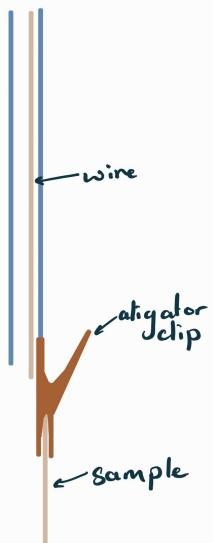


Figure 3: Line drawing of the alligator clip and sample

2.4 Physical Problems with the setup

The existing setup came with an analog voltage supply that was only able to provide analog control of the voltage based on two knobs (a fine and coarse). This control was only fine enough to $\pm 10\text{mV}$ where the derivative of the current with respect to voltage in the relevant regime was $\frac{dmA}{dmV} = \frac{0.3\text{mA}}{1\text{mV}}$. This meant there was poor resolution on the current control with the previous power-supply with a current resolution of $\pm 3\text{mA}$ which would be an insufficient resolution for the small area that was being plated.

I replaced the existing voltage supply with a Tektronics function generator as it provided an appropriate resolution and dynamic range for such the task. The function generator would allow for pulsed plating as recommended by the indium corporation [5]

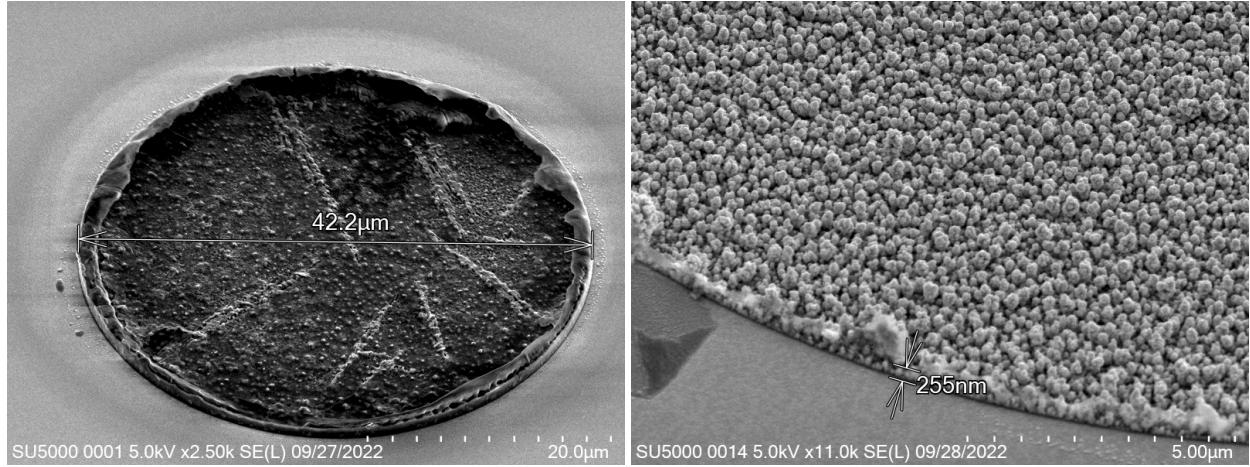


Figure 6: SEM images of indium bumps for 2.4mA current for 5min

2.5 Experimental Issues - Deviation from Theory

According to the Indium corporation docs, the recommended electroplating current density for plating is $10 - 100\text{A}/\text{ft}^2$ at $20\text{A}/\text{ft}^2$ we should observe plating growth at $1.5\frac{\text{mm}}{\text{h}}$. Converting to SI units from ASME units we see that this yields a plating current of $J_{Plating} \approx 0.11 - 1.1\frac{\text{mA}}{\text{mm}^2} \rightarrow I_{Plating} = 2.907\text{mA}$. However, in this analysis we have only considered the active plating area of the sample, and we have failed to consider the plating area of the exposed alligator clip that holds the sample.

The extra exposed area guarantees an incorrect characterization of the plating growth proportional to the exposed area for the indium bumps. We can show this simply from the following

$$\begin{aligned} V &\doteq IR \\ I_{Plating} &\doteq J_{Plating} \times A_{Plating} \\ R_{Total} &\doteq R_{Anode} + R_{PlatingSolution} + R_{Cathode} + R_{Wires} \\ V_{Plating} &\doteq \text{Variable to satisfy plating current} \end{aligned} \tag{A}$$

From the datasheets from Indium Corporation [6] we see that the recommended plating current density.

$$J_{Plating} = 10 - 100\text{A}/\text{ft}^2$$

Or in more elegant units:

$$J_{Plating} \approx 0.11 - 1.1\frac{\text{mA}}{\text{mm}^2}$$

We can then solve for the plating current based on the exposed area given by the GDS file of the sample in figure 5.

The exposed area is thus:

$$\begin{aligned} A_{Plating} &= \pi(20\mu\text{m})^2 + (4.5\text{mm} \times 3\text{mm}) \\ &\approx 13.5\text{mm}^2 \end{aligned}$$

Thus, the plating current for a current density of $20\text{A}/\text{ft}^2$ or $0.2153\frac{\text{mA}}{\text{mm}^2}$ which represents a growth rate of $1.5\frac{\text{mm}}{\text{h}}$ or $25\frac{\mu\text{m}}{\text{min}}$ is as follows.

$$\begin{aligned} I_{Plating} &\doteq J_{Plating} \times A_{Plating} \\ I_{Plating} &= (0.2153\frac{\text{mA}}{\text{mm}^2}) \times (13.5\text{mm}^2) \\ I_{Plating} &= 2.907\text{mA} \end{aligned}$$

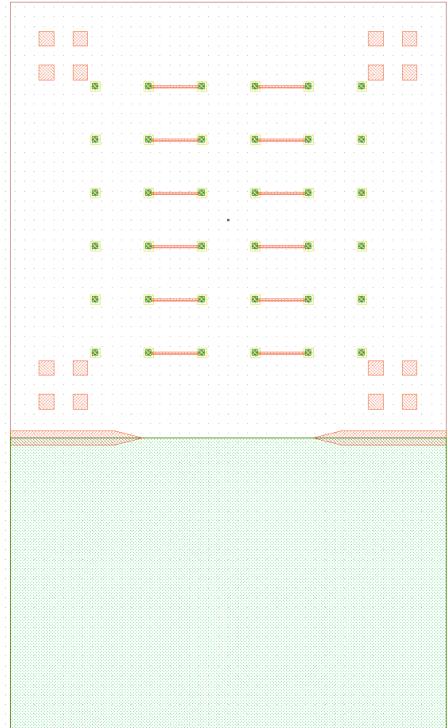


Figure 5: GDS image of the layout. Indium is in green bumps have a diameter of 40 μm

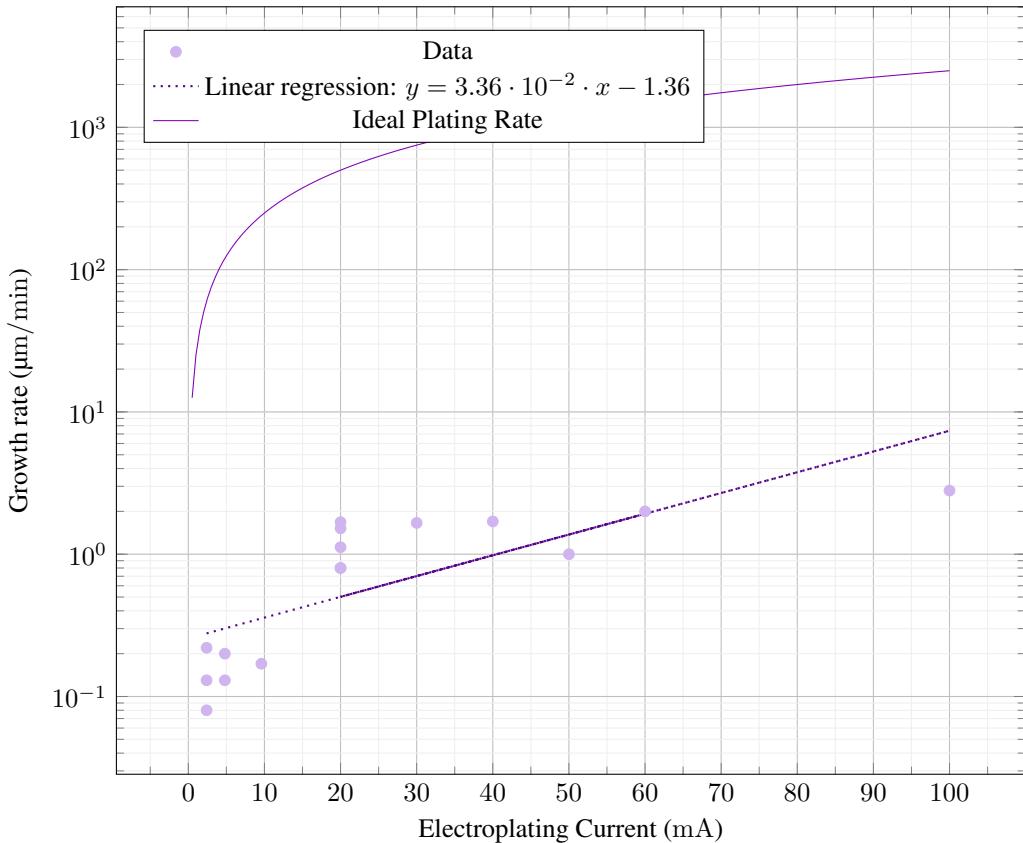


Figure 7: A scatter plot of current vs growth rate.

However, when we apply a voltage of 2.4mA for 5 minutes the growth we see in figure 6 that the growth is between $0.3 - 1.2\mu\text{m}$ in thickness.

From those results we can see that the estimate of area that we predicted we got $\frac{0.8}{25} \times 100\% = 3.2\%$ of the expected growth. While that is not explicitly a problem, the indium bumps and growth did not look very uniform or nearly thick enough compared to what would be needed in the proceeding steps.

From here a number of more experiments were conducted and condensed results of the growth were compiled in the table 2

2.6 Development of a Repeatable Process

In summary, the highlighted issues here have to do with the excessive easy by which the sample holder assembly floats on the beaker, this can in instances cause significant change in the plating rate as seen by the large variance in plating rate as seen in the scatter plot figure 7. I must ensure that the sample is well aligned and distanced appropriately from the indium anode to minimize confounding factors.

Secondly in this section we improved plating current control with the use of a digital function generator and an ammeter in series. With this control of the plating current density was significantly improved by almost 1 order of magnitude.

Sample Name	Electroplating Time (min)	Electroplating Current (mA)	Indium Thickness (μm)	Growth rate ($\mu\text{m}/\text{min}$)
01-Caesar	5	2.4	1.1	0.22
02-Augustus	5	2.4	0.4	0.08
03-Tiberius	10	2.4	1.3	0.13
04-Caligula	5	4.8	1	0.2
05-Claudius	10	4.8	1.3	0.13
06-Nero	10	9.6	1.7	0.17
07-Galba	5	50	5	1
08-Otho	5	100	14	2.8
09-Vitellius	5	20	8.4	1.68
10-Vespasian	5	30	8.3	1.66
11-Titus	5	40	8.5	1.7
12-Domitian	5	60	10	2
13-Nerva	5	20	7.6	1.52
14-Trajan	5	20	5.6	1.12
15-Hadrian	5	20	4	0.8
16-Pius	5	20	4	0.8

Table 2: Table of condensed results of Phase 1 plating experiments

3 Phase 1 - Uniform Bonding

3.1 Characterization of Indium Bonding Spread

After a repeatable electroplating process for indium was developed, the next step was to investigate how the indium would spread once die-bonded. The spreading behaviour of indium is critical because it can impact the performance of the semiconductor device. Specifically, the spreading of indium can affect the heat dissipation and the electrical contact between the die and the substrate. Understanding this behaviour is essential for optimizing the performance of the device. This knowledge can then be used to inform the design and manufacture of semiconductor devices, improving their reliability and performance. Diebonding is the process of placing a semiconductor chip onto a substrate or package, and eutectic bonding is a common diebonding technique. Understanding the behaviour of indium during eutectic bonding is crucial for ensuring the reliability and performance of the final device.

4.80		5.22			3.98	4.05			5.32		5.33
					3.33	4.85					
2.61			3.18					4.81			5.40
3.02		3.11			3.88	5.29			3.78		3.88
6.55		12.0			18.1	4.94			4.55		5.01
6.15			6.28		8.82						6.04
						4.95			4.67		
6.21		11.1			8.57	5.08			5.54		5.99

Table 3: Indium bump height map

A flipchip diebonder is a machine that is used to bond microelectronic chips directly onto a substrate. It allows for precise alignment and bonding of the chip to the substrate, which is essential for the proper functioning of microelectronic devices. In addition to the standard bonding techniques, a flipchip diebonder with eutectic bonding capabilities enables the bonding of two chips by bonding with precise control of heat and pressure, which can greatly enhance the reliability and performance of the microelectronic device. Eutectic bonding is a specialized technique that involves heating the two materials to their eutectic point, at which they melt and fuse together, creating a strong and reliable bond. This makes the flipchip diebonder with eutectic bonding capability a valuable tool in the field of microelectronics for high-performance and reliable bonding of chips to substrates.

The diebonder being used is the ‘TRESKY-diebond’ tool in the QNC packaging lab it is the Tresky T-3000-FC3 model. The tool is capable of providing a bonding force of up to 490N (50kg mass) may be applied at temperatures up to 400°C. The datasheet suggests that it offers placement accuracy of 10µm [7].

The current process of diebonding is

Since we want to calculate and understand how the indium will conform when bonding is done, a number of characterization measurements were conducted to understand how the indium will spread and expand over the sample surface.

Since the volume of indium will not change when diebonding occurs, we can model the spread of indium as a flattening of a cylinder.

16.4		18.7			16.5	16.1			16.5		16.0
					16.1	16.0					
17.1			16.3					15.4			15.9
17.0		16.7			15.6	16.3			15.4		15.8
14.9		21.8			25.6	18.0			19.5		17.6
19.7			19.3		20.8						19.7
						18.7			19.5		
20.4		21.8			17.2	20.1			22.2		21.4

Table 4: Indium bump width map

$$\begin{aligned}
 V_{CylinderInitial} &= V_{CylinderFinal} \\
 \pi \times r_{Initial}^2 \times h_{Initial} &= \pi \times r_{Final}^2 \times h_{Final} \\
 \sqrt{\frac{h_{Initial}}{h_{Final}}} r_{Initial} &= r_{Final} \\
 \sqrt{\frac{h_{Initial}}{0.65\mu\text{m}}} r_{Initial} &= r_{Final}
 \end{aligned} \tag{B}$$

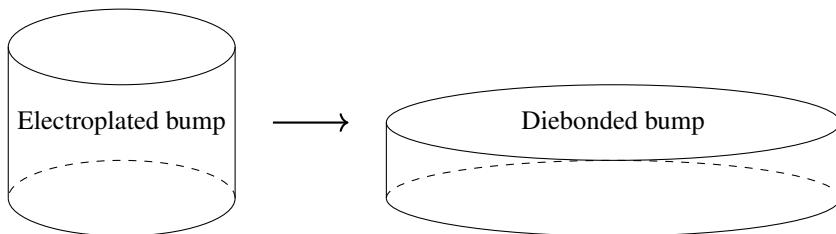


Figure 8: Line drawing of the change in shape of indium shape (not to scale).

The spread values were identified from images taken from the microscope ‘OLYMPUS-scope3’ in the packaging lab.

From the images captured by the scope 10, we can see that the gimble head in the lab provides sufficiently uniform bonding pressure over the bonding area. The images also show that there is spreading of the indium as the bond is formed directly as a function of the indium volume.

Knowing that the bond does spread will constrain the maximum density of μ LEDs for a given bump thickness.

Based on a number of bonding experiments I determined that the average thickness of indium after bonding was around $65\mu\text{m}$ a sample of the indium bump can be seen in figure 9

The raw data from which I determined the average indium thickness is from table 6.

From the table after removing outlier values, the median resulting thickness is $65\mu\text{m}$.

1014		1434			851	819			1131		1072
					678	975					
599			664					896			1065
685		681			742	1097			704		761
1142		4479			9316	1257			1352		1212
1875			1828		2995						1832
						1359			1395		
2030		4145			1979	1604			2135		2144

Table 5: Indium bump volume map

3.2 Thermal Simulations

Thermal simulations were conducted because there were some bonding failures seen in the samples. As can be seen from SEM images and Energy-dispersive X-ray spectroscopy (EDX or EDS) the indium does not always appropriately wet onto the other substrate being bonded onto this is seen in the SEM images in figure 11 and EDX images in figure 12. There can be various reasons why indium does not wet onto a surface during diebonding. One reason could be the presence of surface contaminants such as oxides or oils, which can prevent the indium from bonding to the surface. Another reason could be an insufficient amount of heat or pressure during the diebonding process, which can cause the indium to not properly wet onto the surface. Additionally, the surface energy of the substrate can also affect the ability of indium to wet onto the surface during diebonding.

To explore further a lack of heat, thermal simulations were conducted to identify if a process change in the diebonding preocess was required. Thermal simulations were done in MATLAB with the following code in Appendix B.

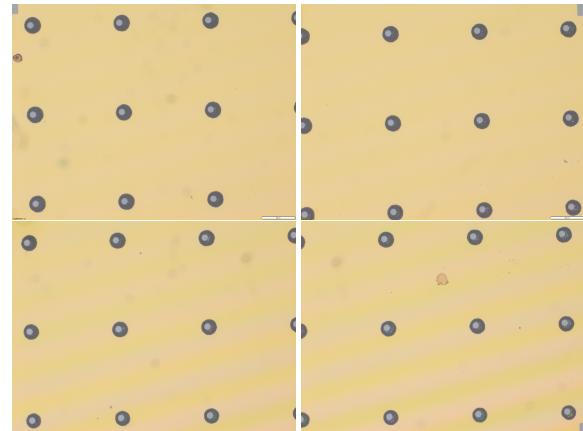


Figure 10: Microscope images of diebonded sample. The internal smaller circles seen are a diameter of $42\mu\text{m}$ the larger circles are the indium spreading

Bond ID	In Bond Avg. Diameter (μm)	Indium Thickness (μm)	In Bump Width (μm)	In Bump Volume (μm ³)	Bond Estimated Thickness (μm)
BID-005	58.6	1.3	42	1801	0.667
BID-006	84	1.7	42	2355	0.425
BID-008	200	1.4	42	19396	0.617
BID-009	86	8.4	42	11637	2.003
BID-010	105	8.3	42	11499	1.328
BID-011	142	8.5	42	11776	0.743
BID-012	164	10	42	13854	0.655

Table 6: Table of estimated thickness post diebonding

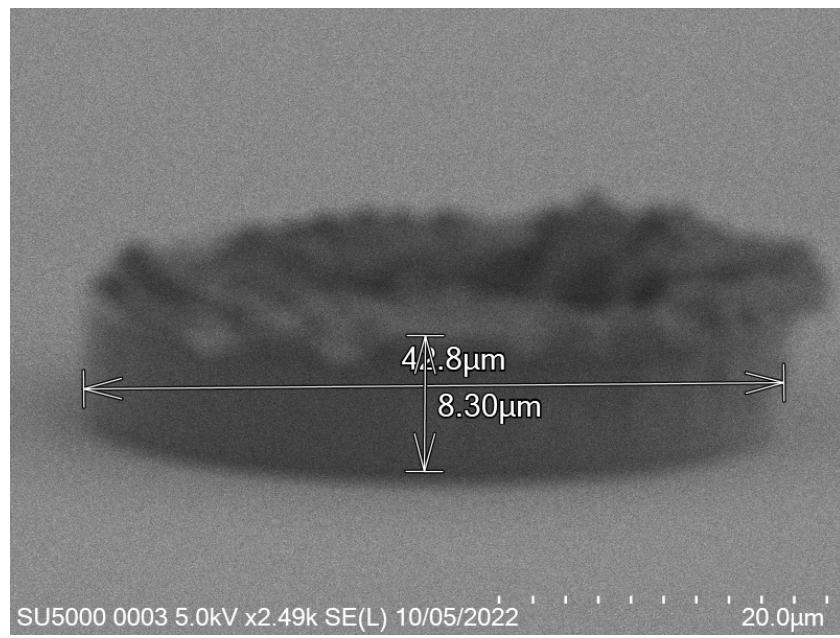


Figure 9: SEM image of indium bump at an angle of 80°

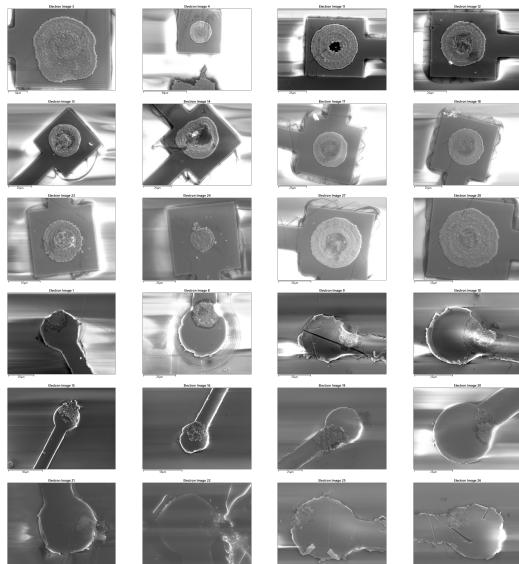


Figure 11: SEM Images of bonds

The results from the thermal simulations as seen in figure 13 in MATLAB were that there was more than sufficient time and heat to melt and wet the indium onto the opposing surface. As a result the lack of wetting was likely a result of one of the other issues (contaminants from the flip-chip process or some failure in the surface energies). Both of the other issues are quite possible as during the process the substrate that is bonding onto the substrate with indium on the surface is face down on the ‘diebonder’ which is a unclean surface that also does not have the appropriate surface energies and could dissipate the surface energy generated during the plasma cleaning process.

It can be seen from the thermal simulations that the time taken for the indium to reach temperature is well within 0.3s whereas the bonding recipe calls for the sample to sit at 250°C for 5min. This is well within 2 orders of magnitude of time for the sample to reach temperature, as such it would be safe to assume that heat/temperature or lack thereof is not the causal source of failure.

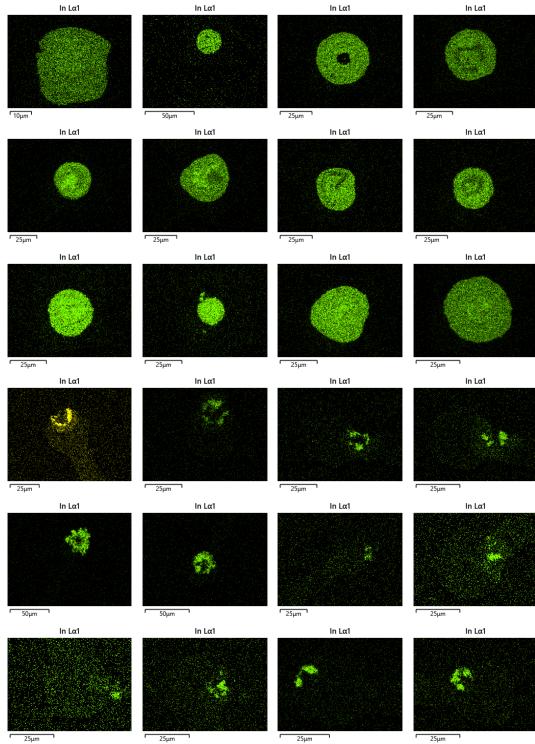
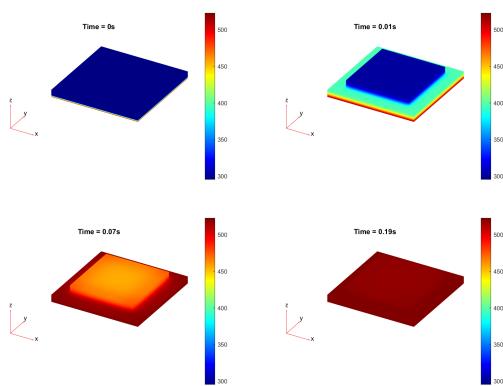


Figure 12: EDX Images of bonds

3.3 Conformation to Theory



Conformed to theory when the bonding would spread according to the calculated volume

3.4 Development of a Repeatable Process

Figure 13: Thermal simulation results. Temperature scale is ranged from 25°C to 250°C

4 Phase 2 - Electrical Connection

4.1 Characterization of Electrical Connection

Conducting the daisychain test

4.2 Connection Issues

did not connect at first,
adjusted process to not do hmds

4.3 Conformation to Theory

4.4 Development of a Repeatable Process

5 Phase 3 - Bonding to LEDs

5.1 Bonding Issues

5.2 Lighting Issues

5.3 Conformation to Theory

5.4 Development of a Repeatable Process

6 Addendum - Driving Displays

6.1 Passive Matrix Displays

6.2 Active Matrix Displays

6.3 Designs for In-House drivers

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7 Appendix

7.1 Appendix A - Standard Operating Procedure Electroplating E3

Note: Electroplating procedure used in the E3-3139 Lab

1 Purpose

Depositing Indium from an electroplating solution onto samples for die-bonding. The solution used is from Indium Corporation of America and uses their Indium Sulfamate Plating Kit to perform the Indium electroplating.

2 Equipment

Name	Quantity
Fume Hood	1
N2 Gun	1
DI Water Bottle	1
2L Beakers	2
400mL Beaker	1
200mL Beaker	1
1L HDPE Bottle	1
500mL HDPE Bottle	1
Hotplate with Magnetic Stirring	1
Magnetic Stir Bar	1
Funnel	1
Insulated Copper Wire	2
Banana Plug Wires	2
Copper Alligator Clips	2
Tweezers kit	1
Custom Sample Holder	1

Name	Quantity
Indium Sulfamate Plating Bath	1L
Indium Anode (30 cm x 2.5 cm x 1.5 mm)	1
Sulfamic Acid	150mL
15-20% HCl	150mL
DI Water	10L
pH Paper Set or pH Meter	1
Clean Room Wipes Pack	1

3 Chemical Hazards

No new chemicals are being introduced into the lab, and the SDS of the chemicals relevant to the experiment are attached with the following SOP.

- Sulfamic Acid
- Indium Sulfamate Plating Bath

4 Safety Procedure

- Lab apron, rubber gloves, safety goggles, face-shield, and closed-toed shoes must be worn before interacting with any chemicals
- To avoid spills ready all beakers and bottles under the fume-hood over clean room wipes before opening
- Use care when opening and pouring chemicals to avoid spills during the preparation and process of the experiment

- Do not touch your face or exposed skin during the process of the experiment
- Always wash hands after handling any chemicals or materials
- Avoid inhaling the mist or vapour of the chemicals, and avoid exposure to eyes and skin
- Perform the entire experiment under a fume hood

5 Process Flow

1. Prepare the fume hood surface:
 - (a) Place clean room wipes on the surface of the fume hood.
 - (b) Ensure your name and contact information are visible at the work location in case people need to contact you.
 - (c) Chemicals in the beakers should be identified, and all beakers should be labelled with what chemicals will be in them.
2. Place the digital hotplate with stirring functionality inside the fume hood.
 - (a) Do not place a wipe on the hotplate surface. This interferes with the transmission of heat to the beaker and its contents. It may also present a fire hazard. This is regardless of whether the heating element will be used.
 - (b) Do NOT turn on the heating element over the course of this experiment.
3. Set all four beakers (2x 2L, 1x 400mL, 1x 200mL) under the fume hood, and set one 2L beaker on the hotplate. Place the stir bar inside the beaker on the hotplate.
4. Build the Custom Sample Holder and place in the beaker on the hotplate at the appropriate distance for the electroplating process (5 cm).
5. Place the indium anode into the beaker on the hotplate, ensure that there is an appropriate distance from the sample and ensure that the electrode is connected to an alligator clip. Be sure to use fresh gloves when handling the indium electrode to avoid contamination.
 - (a) Anode/cathode distance may alter grain size and uniformity of electroplating.
 - (b) It is essential that the sample is perpendicular to the normal of the anode (indium)
6. Ensure that all PPE is worn appropriately, and no skin is exposed.
7. Acquire the indium sulfamate solution, sulfamic acid, and diluted HCl solutions from the Acids cabinet and transport it to the fume hood.
 - (a) Pour the indium sulfamate solution into the beaker on the hotplate.
Ensure that the hotplate is OFF and the beaker is at room temperature to avoid shattering glass
 - (b) Pour the sulfamic acid into the 200mL beaker
 - (c) Pour the HCl dilution into the 400mL beaker
 - (d) Pour 2L of DI water into the remaining large beaker
 - (e) Turn on stirring to 300RPM
8. Check the pH of the indium sulfamate solution and verify it is between 1.5 and 2. If the pH exceeds 2 titrate sulfamic acid and mix until the pH enters the range again.
 - (a) Titration of sulfamic acid into the indium sulfamate solution can be done using a pipette that is labelled and only to be used for sulfamic acid. Since the exact pH is not important titration with a pipette is sufficient and a buret is not required.
 - (b) Note that all tools used in the titration process must be rinsed with DI water and dried with N2.
9. Power should ideally be supplied with a pulsed constant current source and set to values in accordance with current over the plating surface area.

- (a) Ensure that the power supply is set and ready but disconnected from the sample now.
 - (b) Measure the surface area of the sample and validate that current supplied to the sample is nominal to $10 - 20A/ft^2$ or $0.01 - 0.02A/cm^2$. For the current design this corresponds to nominal values of (0.02A, 0.1V)
 - (c) Power should be connected as NEGATIVE terminal to sample and POSITIVE terminal to indium anode
 - (d) Electroplating time is a function of the current density and expected final thickness of the deposited indium.
10. Rinse the sample with DI water, place into HCl solution for the activation time (5 min), rinse again with DI water, and place into the sulfamic acid solution for cleansing (3 min).
- (a) The sample should be attached to the custom holder
 - (b) The HCl solution is required for cleaning and acid-activation (see the guide to indium plating).
 - (c) The sulfamic acid ensures the pH of the base metalization surface remains acidic and no reformation of oxide occurs.
11. Place the sample into the plating bath at the appropriate distance and turn on the power supply for the target plating time.
- See the Indium electroplating guide for more information on how this affects the grain size

– Waste disposal, storage instructions for equipment and materials, emergency procedures, and MSDS can be found in the original electroplating SOP document. They were not attached for brevity

7.2 Appendix B - Thermal Simulation Code

```

%% Define Constants
BP_width = 6.2 * 10^-3; % m
BP_length = 6.2 * 10^-3; % m
BP_thickness = 500 * 10^-6; % m

LED_width = 4.5 * 10^-3; % m
LED_length = 4.5 * 10^-3; % m
LED_thickness = 500 * 10^-6; % m

% http://www.roditi.com/SingleCrystal/Sapphire/Properties.html
SAPPHIRE_THERMAL_CONDUCTIVITY = 25.12; % W / m*K
SAPPHIRE_MASS_DENSITY = 3980; % kg / m^3
SAPPHIRE_SPECIFIC_HEAT = 750; % J / kg * K

AMBIENT_TEMPERATURE = 273.15 + 22; % K
HOTPLATE_TEMPERATURE = 273.15 + 250; % K
CONVECTION_COEFFICIENT_AIR = 5; % Unitless nominal 1-5
% https://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html
EMISSIVITY_COEFFICIENT_SAPPHIRE = 0.8;

%% Define 2D geometry
pderect([(-BP_width/2) (BP_width/2) (-BP_length/2) (BP_length/2)], 'BP')
pderect([(-LED_width/2) (LED_width/2) (-LED_length/2) (LED_length/2)], 'LED')
%% Export the geometry description matrix, set formula, and name-space matrix into the
MATLAB workspace by selecting
%%%%%%% Draw > Export Geometry Description, Set Formula, Labels.
% This data lets you reconstruct the geometry in the workspace.

%% Start 3D geometry
g = decsg(gd,sf,ns);
pdegplot(g,"FaceLabels","on")
model = createpde("thermal","transient");
g = geometryFromEdges(model, g)
% Extrude BP
g = extrude(g, BP_thickness);
% Plot
f = figure('Name', 'Geometry');
pdegplot(g,"FaceLabels","on")
view([45 45])

%% Extrude LED
g = extrude(g, 4, LED_thickness);
close(f)
f = figure('Name', 'Geometry');
pdegplot(g,"FaceLabels","on")
view([45 45])

%% Assign geometry to thermal model
model.Geometry = g;
close(f)
f = figure('Name', 'Geometry');
pdegplot(g)

%% Setup Thermal model
thermalProperties(model, ...
    "ThermalConductivity", SAPPHIRE_THERMAL_CONDUCTIVITY, ...
    "MassDensity", SAPPHIRE_MASS_DENSITY, ...
    "SpecificHeat", SAPPHIRE_SPECIFIC_HEAT)
model.StefanBoltzmannConstant = 5.670367e-8;

% Apply heat to the bottom 2 faces

```

```
thermalBC(model,"Face", [1 2] , "Temperature", HOTPLATE_TEMPERATURE);
thermalBC(model,"Face", 3:g.NumFaces, ...
    "ConvectionCoefficient", CONVECTION_COEFFICIENT_AIR, ...
    "AmbientTemperature", AMBIENT_TEMPERATURE, ...
    "Emissivity",EMISSIVITY_COEFFICIENT_SAPPHIRE);

thermalIC(model,AMBIENT_TEMPERATURE);

generateMesh(model);

%% Perform computation for transient thermal analysis
results = solve(model,0:.01:0.3);
%% Plot
for i = 1:length(results.SolutionTimes)
    f = figure(i+5);
    pdeplot3D(model,"ColorMapData",results.Temperature(:,i))
    % clim([AMBIENT_TEMPERATURE HOTPLATE_TEMPERATURE])
    title({'Time = ' num2str(results.SolutionTimes(i)) ' s'});
    saveas(f, [num2str(i, '%03.f') '.png']);
end
```

7.3 Appendix C - Python Code

```
import unittest
class TestSum(unittest.TestCase):
    def test_sum(self):
        self.assertEqual(sum([1, 2, 3]), 6, "Should be 6")

if __name__ == '__main__':
    unittest.main()

$ python test_sum_unittest.py
.F
=====
FAIL: test_sum_tuple (__main__.TestSum)
-----
Traceback (most recent call last):
  File "test_sum_unittest.py", line 9, in test_sum_tuple
    self.assertEqual(sum((1, 2, 2)), 6, "Should be 6")
AssertionError: Should be 6
-----
Ran 2 tests in 0.001s

FAILED (failures=1)

$ pip install nose2
$ python -m nose2
.F
```
