# Sapphire flip-chip thermocompression and eutectic bonding for dielectric laser accelerator

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**Abstract:** Dielectric laser accelerator (DLA) is a potential alternative to traditional radio frequency (RF) accelerator facilities. Chip to chip bonding to form double grating DLA structure is essential, especially for relativistic DLA. Both Au/Au thermocompression and Au/Sn eutectic bonding are successfully demonstrated in this report. Au/Sn eutectic bonding shows a better bonding strength than Au/Au thermocompression bonding for this bonder. Optimized recipes for both bonding techniques are presented.

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## References

1. Breuer, John, and Peter Hommelhoff. "Laser-based acceleration of nonrelativistic electrons at a dielectric structure." *Physical review letters* 111.13 (2013): 134803.
2. Leedle, Kenneth J., et al. "Laser acceleration and deflection of 96.3 keV electrons with a silicon dielectric structure." *Optica* 2.2 (2015): 158-161.
3. Leedle, Kenneth J., et al. "Dielectric laser acceleration of sub-100 keV electrons with silicon dual-pillar grating structures." *Optics letters* 40.18 (2015): 4344-4347.
4. https://en.wikipedia.org/wiki/Thermocompression_bonding
5. Matijasevic, Goran S., Chin C. Lee, and Chen Y. Wang. "Au/ Sn alloy phase diagram and properties related to its use as a bonding medium." *Thin Solid Films* 223.2 (1993): 276-287.

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## 1. Introduction

Miniaturized sources of energetic electrons with sub-femtosecond temporal control has the potential to benefit several areas of science and technology, including ultrafast measurements, ultrafast electron diffraction, x-ray generation and medical radiation therapy. Dielectric laser accelerators (DLA) promise to enable miniaturized electron sources with high timing precision, owing to the high electric fields and great temporal control that can be realized with ultrafast lasers than with conventional RF sources. In principle, greater than two orders-of-magnitude higher acceleration gradient (energy gain per distance [MeV/m]) is possible with DLAs as compared with traditional RF accelerators. DLA paves the way for a new class of simple yet powerful devices with applications in ultrafast science, optics, and biomedicine.

Several acceleration experiments have already been demonstrated with DLA made of silicon and fused silica substrate [1,2,3]. In this report, we present to use sapphire as the potential candidate material because of its higher laser induced damage threshold (LIDT), which indicates higher acceleration brought by the fact that higher LIDT means it could be driven by higher laser power. Inverse Smith-Purcell grating (single grating) is able to accelerate sub-relativistic electrons with an exponential decay mode that travels at the same speed with electron. However, this mechanism does not apply to relativistic electrons (electron with energy larger than 1MeV). For relativistic electrons, it is necessary to have the second boundary condition to have an accelerating mode, requiring a closed structure, such as double grating structure. In order to fabricate such a double grating, the easiest way is to fabricate two halves and bond them together, rather than monolithically fabricate it in one wafer. This is due to the fact that sapphire is very difficult to etch. Figure 1 shows the schematic of the structures for our devices.

We firstly briefly introduce Finetech FINEPLACE Lamba Bonder. Using this tool, we investigate two bonding techniques, gold to gold thermocompression bonding and gold to tin eutectic bonding. Finally, we utilize the calibrated bonding recipes along with HDPCVD deposited silicon dioxide spacer layer, which is used to accurately controlling the gap between two sapphire chips, to form a bonded sapphire based DLA.

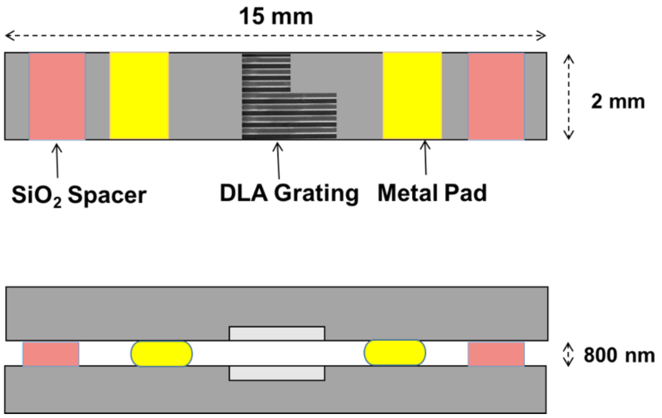

Figure 1. Schematic of bonded sapphire chips: top view and cross-section view.

## 2. Finetech FINEPLACE Lambda Bonder Overview

Finetech FINEPLACE Lambda Bonder, shown in Figure 2, is a flip-chip bonder with a fixed beam splitter to achieve an overlaid vision alignment system, allowing sub-micron placement accuracy. The maximum field of view is 6.7mm by 5.4mm.

Figure 2. Finetech FINEPLACE Lambda Bonder.

Basically, two chips are held by vacuum chucks in directions perpendicular to each other, before bringing the chip on a rotatable arm down to meet the second chip. The rotatable arm can be pulled down manually during the bonding process and the load can precisely control the total external force applied to the chips. Bonding force ranges from 0.1N to 20N. Chip size can range from 0.1mm*0.1mm to 15mm*15mm.

Bonding temperature is a critical parameter and the temperature profiles of substrate and the chuck on the arm can be separately tuned by software. The maximum temperature ramping rate is 20K/s for substrate and 6K/s for arm. The maximum allowed temperature is 400˚C. Below 380˚C, we are allowed to heat the sample continuously. Between 380˚C and 400˚C, heat time must be limited to less than 2 minutes. There is an optional $N_2$ box associated with this bonder to prevent local moisture and oxidizing.

## 3. Au/Au Thermocompression Bonding

Thermocompression bonding is a wafer bonding technique and is also referred to as diffusion bonding, pressure joining, thermocompression welding or solid-state welding. Two metals, e.g. gold (Au)-gold (Au), are brought into atomic contact by applying force and heat, simultaneously. The diffusion requires atomic contact between the surfaces due to the atomic motion. The atoms migrate from one crystal lattice to the other one based on crystal lattice vibration [4]. This atomic interaction sticks the interface together.

With 20nm Ti followed by 450nm Au deposited by Innotec, a e-beam evaporation tool in SNF, on sapphire as intermediate layers by innotec, two sapphire chips are bonded with the bonding temperature profile is as shown in Figure 3.

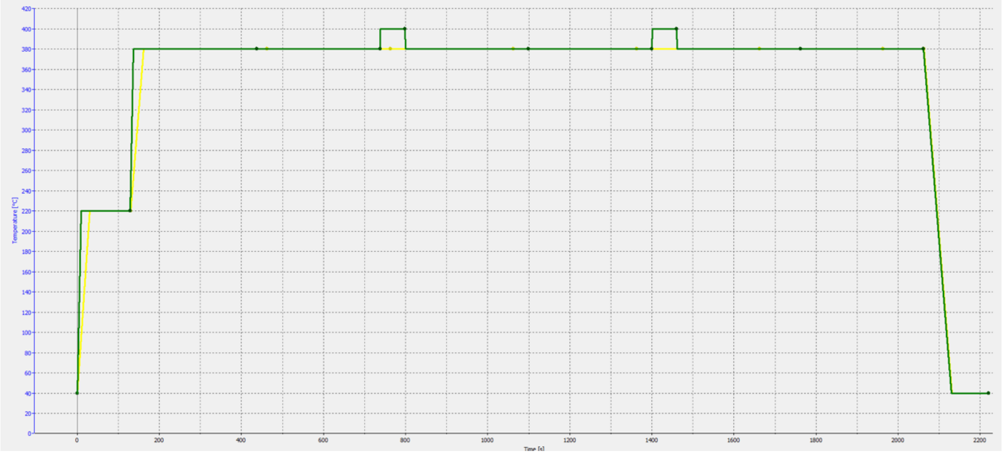

Figure 3. Au/Au thermocompression bonding temperature profile.

The sample is preheated to 220℃ and stabilize for 10 minutes to minimize the temperature difference between two arms. In everyone ten minutes duration of heating at 380℃, the substrate and arm is heated up to 400℃ for 1 minute. The overall heating time is 45 minutes. We measure that the real temperature at the interface is usually 40˚C lower than the assigned temperature shown on the software due to the limited thermal conductivity of sapphire. This characterization is measured with thermal coupler associated with the tool. We encourage future users to characterize the temperature first.

We did three categories of experiments using the same temperature profile with the external bonding force of 20N. For the first category, we only use acetone and isopropanol to clean the sample. The chip size is 8mm*15mm, indicating a pressure of 166KPa, smaller than the recommended pressure for Au/Au thermocompression bonding (1MPa). The first category did not achieve a reasonable bonding strength as expected.

**Table 1. Au/Au Thermocompression Bonding Results Summary**

| | **cleaning** | **pressure** | **bonding** |
|---|---|---|---|
| 1st | x | 166KPa | x |
| 2nd | ✔ | 166KPa | ✔ |
| 3rd | ✔ | 1MPa | ✔✔ |

In second category, we did more thorough cleaning by using $O_2$ plasma with the descum recipe in Drytek2 followed by SRS-100 wet-bench cleaning at 70℃ for 30min, leading to better bonding strength (the chips do not separate during normal handling with tweezers) . To quantitatively characterize the bonding strength, (ExFab/SNF has not purchased or setup a sheer test instrument by the time we finish this project. But we have actively discussed ideas regarding this sheer tests during E241 class) we did simple dropping test by releasing the sample from 15cm and 1.2m to tile floor. The bonded sample survived the 15cm-drop but not the 1.2m-drop.

We expected the bonding strength to increase with higher bonding pressure. Thus we verified this idea by shrinking the chip size from 15mm*8mm to 10mm*2mm in the third category of samples, corresponding to 1MPa pressure on the chip. With the same cleaning procedures and bonding conditions, this third category of chips bonded better. This is demonstrated by the fact that the bonded chips did not separate until dropping from 1.2m-dropping test a second time.

To sum up the Au/Au thermocompression bonding, cleaning is the key factor to achieve a good bonding strength. Higher pressure for thermocompression bonding corresponds to better bonding. Limitations of this process include the high temperature and the long bonding time. Therefore, we continued studying other bonding mechanism, aiming for better bonding strength during shorter bond duration and at lower temperatures.

## 4. Au/ Sn Eutectic Bonding

Eutectic bonding, also referred to as eutectic soldering, describes a wafer bonding technique with an intermediate metal layer that can produce a eutectic system. Those eutectic metals are alloys that transform directly from solid to liquid state, or vice versa from liquid to solid state, at a specific composition and temperature without passing a two-phase equilibrium, i.e. liquid and solid state.

As shown in Figure 4 [5], gold and tin can form a eutectic alloy a much lower temperature than the melting point of gold at 290℃, when the weight ratio between Au and Sn is 4:1 (corresponding film thickness ratio is 1.5:1 given the atomic mass and density of Au and Sn).

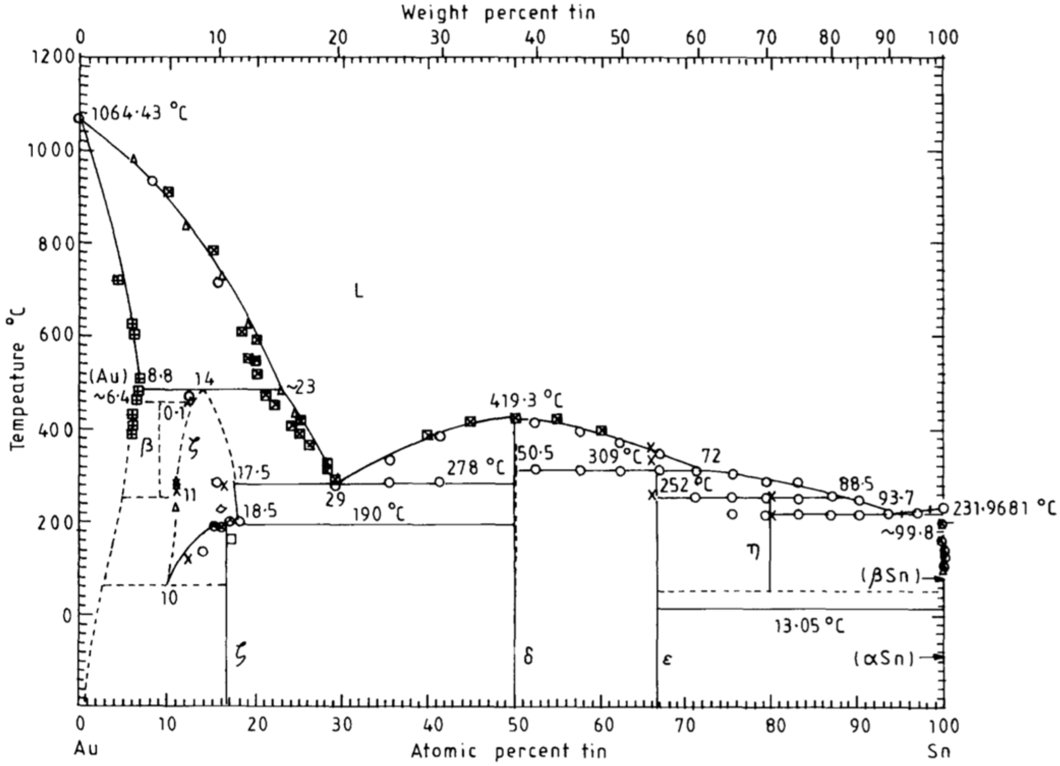

Figure 4. Au/Sn eutectic bonding atomic ratio dependency on temperature.

We deposited metal stacks as follow: 20nm Ti/450nm Au/ 320nm Sn/ 30nm Au using Innotec, a e-beam evaporation tool in SNF. Titanium is the first layer deposited on sapphire wafer, serving as an adhesion and diffusion barrier layer. The top layer of 30nm of gold is critical for preventing the tin from oxidizing, without which good bonding will not be achieved. The sapphire wafer is then diced by wafer saw into chip size of 2mm*15mm before bonding.

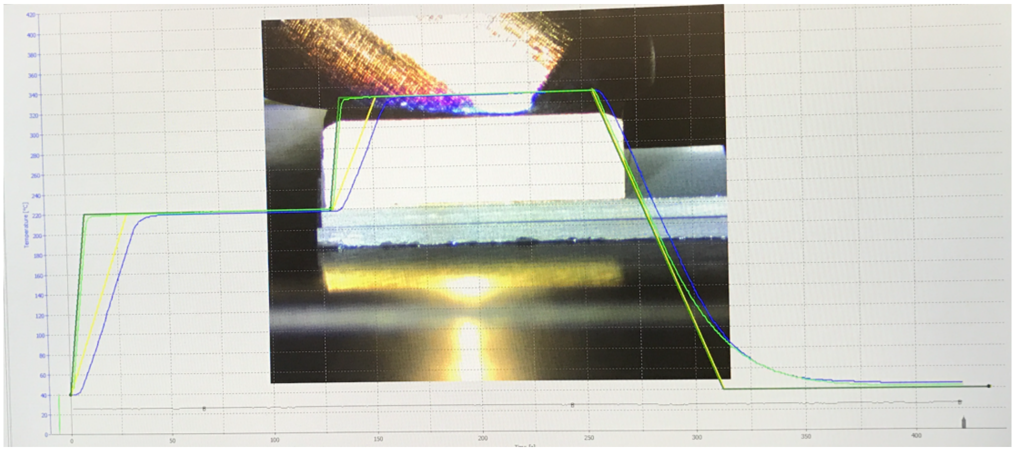

Figure 5. Au/Su eutectic bonding temperature profile.

We followed the same clean procedure and heated up the chips with the temperature profile shown in Figure 5. Since the heating chuck on substrate and the arm have different heating capability, to minimize temperature difference and stabilize the temperature equilibrium the two chips are first preheated to 220˚C for 2min, which is below the melt point of Sn.

**Table 2. Au/Sn Eutectic Bonding 1.2 Dropping Test**

| | **280℃** | **290℃** | **300℃** | **340℃** |
|---|---|---|---|---|
| 5min | 1 | 2 | 2 | 2 |
| 7min | | **5** | 1 | 1 |
| 9min | 1 | 1 | | |

During the heating process, we have clearly observed metal melting and eutectic alloy forming, indicated by the color changes from gray to yellow. In order to find the optimal Au/Sn eutectic bonding recipe, we did a design of experiment (DOE) in terms the bonding time and temperature. As discussed previously, the results of dropping test from 1.2m high to tile floor is recorded in Table 2, where each number means number of times the sample survives before separated. The best condition is at 290℃ for 7min, and the results were consistently demonstrated. We bonded fabricated chips from 4 different wafers at different time within one month. The survived number of drops before separation ranged from 4 to 7. Cleaning is also critical for Au/Sn eutectic bonding, the chips can be very well bonded immediately after SRS-100 cleaning, but not if they were kept in a wafer holder sitting in air for 5 days. For these chips that cannot be well bonded after sitting for 5 days, we re-did the cleaning. The chips can be well bonded again with consistent dropping test results. In Au/Sn eutectic bonding, the top layer of 30nm of Au that is used for preventing Sn from turning into $SnO_2$. This is also critical in achieving a successful bonding. Compared with Au/Au thermocompression bonding, Au/Sn eutectic bonding provide better bonding strength, which is achieved at lower temperature and shorter time.

## 5. Accurately Control the Gap with Spacer

In the experiment of dielectric laser acceleration, the gap between two chips significantly affects the acceleration gradient, and the variation of gap size should be no more than 50nm, which is hard to achieve by only controlling the bonding force. Thereby we introduce a $SiO_2$ spacer layer to accurately control the gap. As shown in Figure 6, the yellow region is 20nm

Ti/450nm Au/ 320nm Sn/ 30nm Au metal stack as described previously and pink region is the 800nm-thick spacer made of $SiO_2$ deposited by HDPCVD. We are planning to bond these two chips, as shown in the schematics in Figure 1.

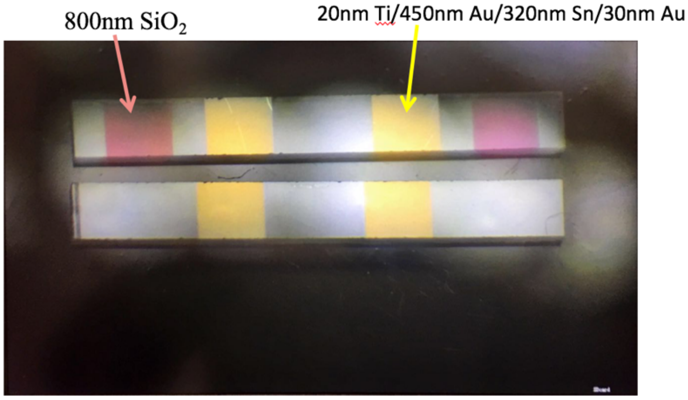

Figure 6. Top view of the bonded chip, where yellow region is metal stack and pink region is $SiO_2$ spacer.

Figure 7 shows the final bonded chip picture from top and side view. From the top view, we can clearly see the interference fringes, which indicates that the gap between two chips is on the order of micro to sub-micron.

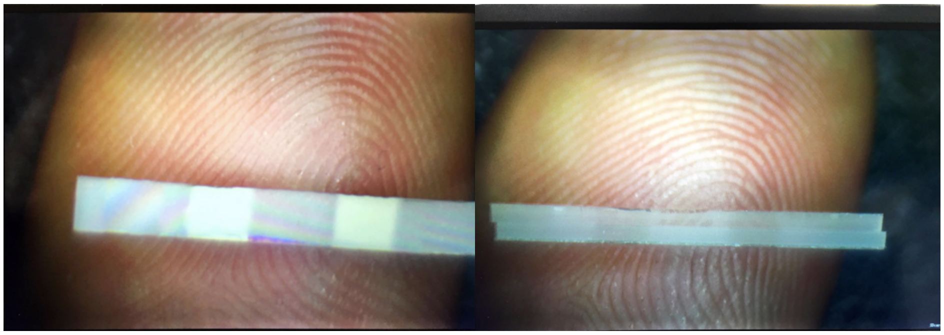

Figure 7. Top view and side view of the final bonded chip with spacer.

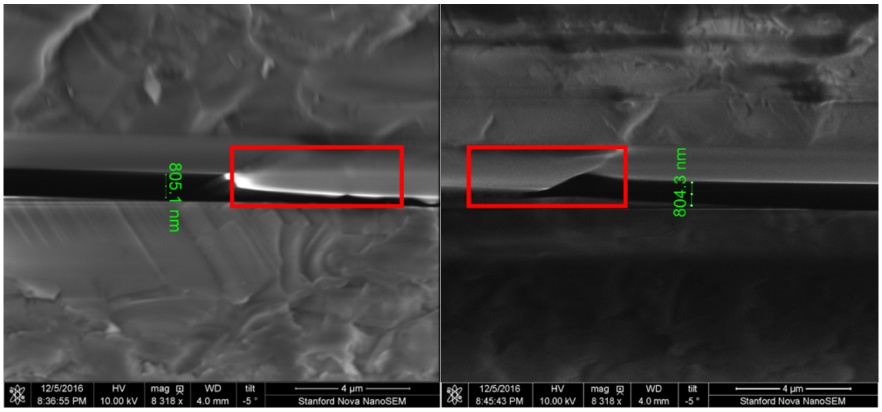

Figure 8. SEM of the left and right side of the space.

We took SEM images for the side view shown in Figure 7. Figure 8 shows the SEM images. The left and right edge of spacer is highlighted with red rectangle (the spacer is too big to be included in one SEM image given the field of view of the SEM system). From the SEM images, we can tell that the gap between two chips is around 804nm, which is only 4nm off from what we designed. We also did the drop test for this bonded chips and they survived 5 times of dropping before separation. This accuracy of gap controlling and bonding strength is good enough for dielectric laser acceleration application.

## 6. Summary

In this report, we have studied Au/Au thermocompression and Au/Sn eutectic bonding techniques, and achieved successful bonding results with both techniques. Cleaning is critical for both thermocompression and eutectic bonding (above mentioned cleaning procedure and proper gowning during bonding experiment). Based on current setup and for this Finetech FINEPLACE Lamba Bonder in ExFab, Au/Sn eutectic bonding works better than Au/Au thermocompression bonding in terms of bonding strength, temperature, and process time. Additionally, thermocompression requires stricter cleaning and higher bonding pressure.

## 7. Acknowledgments

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