Low Thermal Damage Laser Lift-off (LLO) Enabling Multi-Cycle Carrier Wafers Reuse for Advanced Packaging

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Fusion and hybrid bonding are becoming critical enablers in advanced packaging for die-to-wafer (D2W), high-bandwidth memory (HBM), and artificial intelligence (AI) applications. Laser lift-off (LLO) employing short-pulsed IR laser beam provides a clean and efficient method to release permanently bonded Si carrier wafers without need of a glue layer or backside grinding processes. LLO enables multiple carrier wafer reuse cycles, offering significant cost reduction and environmental sustainability benefits. However, LLO may generate the thermal and mechanical stresses during LLO to impact device integrity.

This study investigates thermal damage mechanisms and mitigation strategies for stacked structures during carrier wafer release. Metal silicide phase transitions were characterized by X-ray diffraction (XRD) to detect thermal exposure 200–500 °C, while tracer ion diffusion analysis via time-of-flight secondary ion mass spectrometry (ToF-SIMS) identified thermal exposures in the 800–1000 °C range. These results were calibrated against 60-second rapid thermal annealing (RTA) references to establish a thermal budget for LLO induced energy exposure.

The results of these thermal damage experiments were used to model a broader spectrum of stacked materials. The absorption through the stack and the resulting heat transfer were simulated. Since experimental measurements generally require orders of magnitude for longer timescales than laser exposure, it is challenging to compare the energy spike in LLO simulation to a thermal budget based on RTA processing. If for a given stack it has been demonstrated experimentally that the heat energy from the laser is at an acceptable level, then it is reasonable to assume that other stacks that show equal or less heat energy in simulation are also acceptable. This integrated experimental–simulation framework supports optimized stack engineering, ensuring device integrity and sustainable multi-cycle carrier wafer reuse for advanced packaging.

Keywords: laser lift-off, carrier wafer reuse, thermal damage, hybrid bonding, transient thermal simulation, IR release, phase transformation

I. Introduction

Semiconductor fabrication primarily uses silicon (Si) wafers as substrates for integrated circuit (IC) chips. Temporary and permanent bonding/debonding technologies are essential for enabling wafer stacking in advanced 2.5D and 3D applications, including high-performance computing (HPC), high-bandwidth memory (HBM), and artificial intelligence (AI). In particular, laser lift-off (LLO) uses an infrared (IR) laser to debond a sacrificial layer, allowing the release and reuse of the Si carrier wafer. This method improves power, performance, area, and cost (PPAC) metrics.

In this study, the Si wafer was employed as a carrier wafer after releasing from temporary or permanent bonded wafers. Since an infrared (IR) laser beam can penetrate the electronic bandgap of the Si wafer, the LLO process utilized an optimized engineering layer comprising a sacrificial layer and a release layer. This layer design enabled efficient IR-beam absorption and localized thermal stress. The release layer was selected to prevent IR-laser penetration and protect the underlying device layer.

To understand the thermal damage mechanism during the LLO process, we calculated the thermal damage threshold using laser matter interaction simulations. The simulation results clarified the heating mechanism within the layer and were validated by thermal damage detection. At present, the only quantitative thermal indicator method available relies on a device that measures temperature during rapid pulsed laser processing using a highly localized, micron-scale laser spot. In the conventional approach, thermal damage from pulsed laser processing is assessed by heating known thin-

film materials to their melting points using different laser energies. However, this method lacks the sensitivity required to detect thermal damage caused by rapid laser processing on semiconductor devices (e.g., NANDs and logic devices).

We introduced two quantitative thermal-indicator methods to detect heat generated by rapid pulsed laser processing. The first method determines whether the laser-induced heat exceeds 800 °C by tracking ion diffusion. It evaluates changes in the concentration of ions sensitive to diffusion, produced by the heat of the laser process within the implanted thin-film indicator layer. Time-of-flight secondary ion mass spectrometry (ToF-SIMS) is used to measure concentration depth profiles. The thermal energy deposited in the indicator layer is reflected as a change in the ion profiles, and this change is compared against our established temperature references derived from ion-diffusion profiles. The second quantitative method uses a phase-transformation material as a thermal indicator to detect heat from rapid pulsed laser processing. This method enables temperature detection in the range of 400 °C, which is closer to the relevant accepted thermal budgets.

In this report, we demonstrated multi-cycle carrier wafer reuse during LLO process with low thermal detection with pulsed IR laser.

II. Results

A. Si carrier wafer reuse from bonded wafers by LLO

The released Si carrier wafer's topology was reduced and rebonded onto the device wafer by fusion bonding. Prior to bonding, both wafers were plasma-activated and rinsed to promote the formation of hydrogen bonds between the carrier and device layers. The wafers were then annealed to promote the formation of Si–O covalent bonds at the interface. Fig. 1 shows the rework process steps for rebonding a carrier wafer.

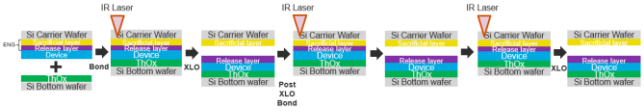


Fig. 1. Reuse of the Si carrier wafer after successive separation by LLO.

The sacrificial layer is a transparent barrier designed to reduce laser-induced topological damage on the carrier wafer during subsequent reuses. The release layer consists of films that are opaque to IR light, preventing laser exposure of the device. It also functions as a thermal insulator, reducing heat during the lift-off process. Chemical mechanical polishing (CMP) is performed on the top wafer to prevent void formation during fusion bonding. After CMP, the carrier wafer is bonded to a test wafer with a thermal oxide (ThOx) layer. During laser ablation, the adhesion between the sacrificial and release layers is reduced.

The wafer is irradiated with laser light, and then a thin blade is inserted between the bonded wafers to separate them. Next, the sacrificial layer is etched away from the carrier wafer.

Engineered sacrificial films were used for laser release, followed by reconstruction of the device layer(s). The bonding process was then repeated using a new bottom wafer. The number of times a carrier wafer can be lifted off depends on the surface damage to the carrier wafer after each lift-off, which was mitigated by the sacrificial films. To optimize carrier-wafer reuse, two inorganic sacrificial films produced under similar laser settings were lifted off, and their topology was characterized using atomic force microscopy (AFM) for Film A and Film B.

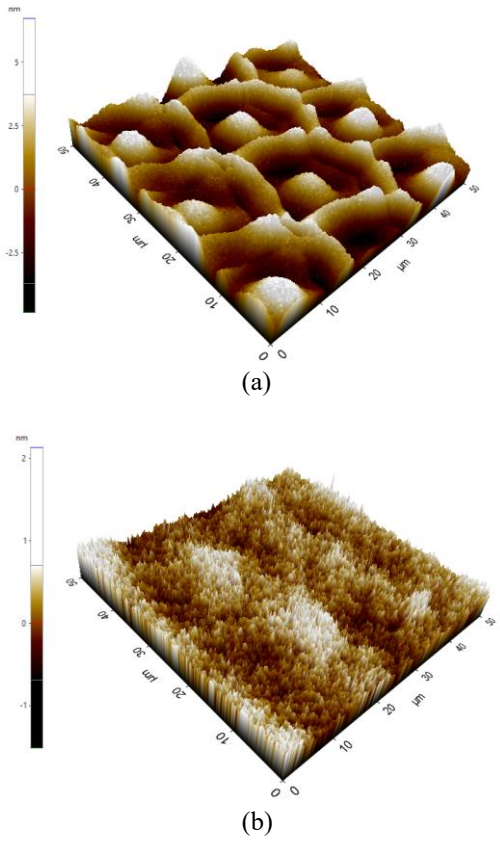
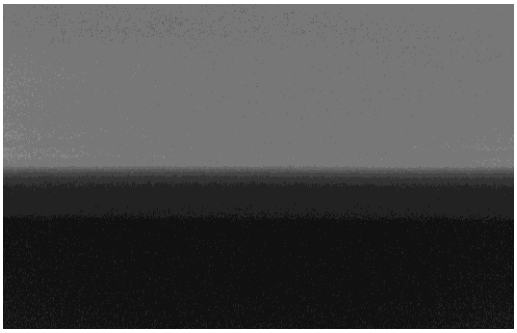


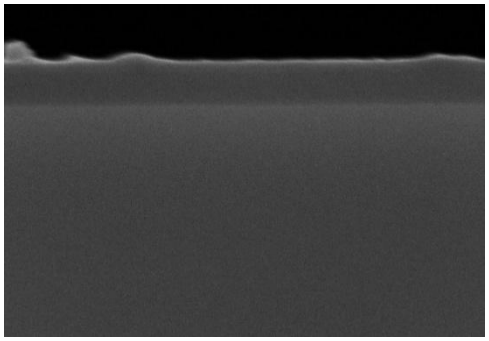
Fig. 2. AFM of sacrificial (a) Films A and (b) Film B after laser lift off. 50umX50um surface area.

Film A had a root mean squared (RMS) roughness of 1.900nm, Film B had RMS roughness of 0.354nm. AFM was done after LLO before rework processing. Film B was determined to be the optimal film for minimizing rework

steps to carrier wafer. Cross sectional Scanning Electron Microscopy (SEM) confirmed separation in between sacrificial layer and release layers of Film A and Film B. Fig. 3 shows cross sectional separation of carrier wafer after LLO.



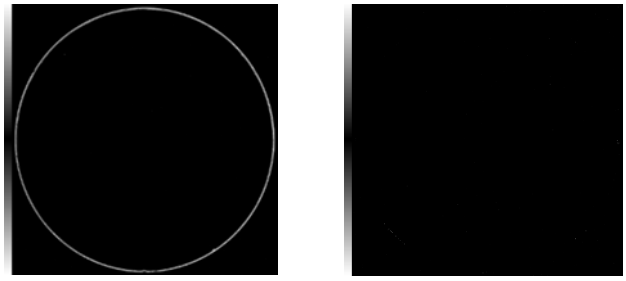
(a)



(b)

Fig. 3. Cross sectional SEM of carrier wafer after lift off sacrificial (a) Film A and (b) Film B.

Where laser separation at the targeted interface occurred in both cases. Reconstructing the engineered stack and device structure of Films A and B resulted in fusion bonded wafers with no voids, confirmed by Confocal Scanning Acoustic Microscopy (CSAM). CSAM showed the results in Fig. 4 (a) and 4 (b) for Films A and B respectively.



(a) (b)

Fig. 4. CSAM showed no voids of rebonded carrier wafers (a) Film A and (b) Film B. Resolution 10um/pixel.

CSAM shows that the reconstructed Film B can be effectively reworked for multiple release cycles. However, cracks can be developed in high-stress regions of the carrier wafer, which limits the number of reuses.

B. Low thermal damage characterization

When the sacrificial film stack was used, thermal simulation showed that most of the heat was kept away from the dielectric layer (thermal indicator layer), and the peak temperature remained below the material's melting point. The absorbance of silicon at the exposure wavelength was initially small but increased exponentially with temperature. This behavior arises because the optical properties must be solved together with the heat-transfer process. After approximately 25 ns of laser exposure, the silicon directly above the layers of interest absorbed sufficient energy that the heat conducted away from the polysilicon exceeded the heat conducted from the overlying layers, resulting in the observed peak.

To optimize reusability of the carrier wafer, the release layer must reduce the thermal stress between the sacrificial and release layers, caused by the thermal gradient between the sacrificial and release layers. Also, the heating effect of the LLO process release layer must be optimized to protect the device from the heat effect of the laser. To that end, two test structures for indirect thermal damage detection have been developed. An ion implantation to detect in the 800-1000°C range and another test structure that can measure in the 400-700°C detection range [7].

The thermal damage characterization methods were selected to assess the thermal safety under external short pulse laser injection. Two processes have been developed for different temperature range. Ion implantation, effective within the detection range of 800°C to 1000°C, was used as a thermal damage indicator layer. The concentration of tracer atoms at specific depths was tracked using time-of-flight secondary ion mass spectrometry (TOF-SIMS) to evaluate laser-induced damage. Comparing the center concentration pre and post anneal, we found the percent change in peak ion concentration. Equation (1) shows peak percentage change before and after processing.

$$\%\Delta\, Concen = \left(\frac{C(z)_{Pre} - C(z)_{Post}}{C(z)_{Pre}}\right) \times 100 \qquad (1)$$

Based on equation (1), reference anneal ion concentration was compared to different release layers to show which release layer to applicable as an insulator. Figure 5 presented TOF-SIMS results, showing a change in peak ion concentration between 800°C and 1000°C, with a linear goodness of fit (GOF) of 92.66%.

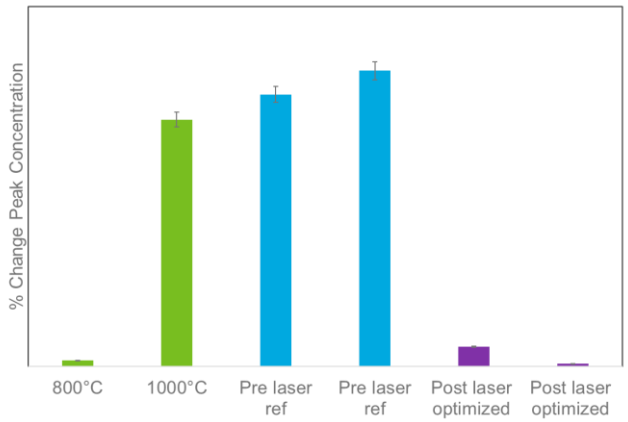


Fig. 5. Peak concentration changes due to TOF-SIMS measurement

Metal silicide was employed for phase transition detection using X-ray diffraction (XRD) at known temperatures, which were then compared to measurements at unknown temperatures. This method could detect the heat in the ranges below 400°C and the range of 400°C < T <700°C. The process can be implemented using rapid thermal annealing (RTA) reference samples, annealed at controlled temperatures to identify corresponding phase changes. XRD patterns obtained from the RTA samples were analyzed to characterize phase transformations in the metal silicide as shown in Fig. 6. Phase A transition was observed at 500°C, followed by the formation of the B phase at 700°C. These phase transformations provide a reliable thermal indicator reference for detecting heat generated during short-pulsed laser processing X-ray Diffraction (XRD) was used for detection under 800°C, which is a more realistic thermal budget for NAND and logic cells.

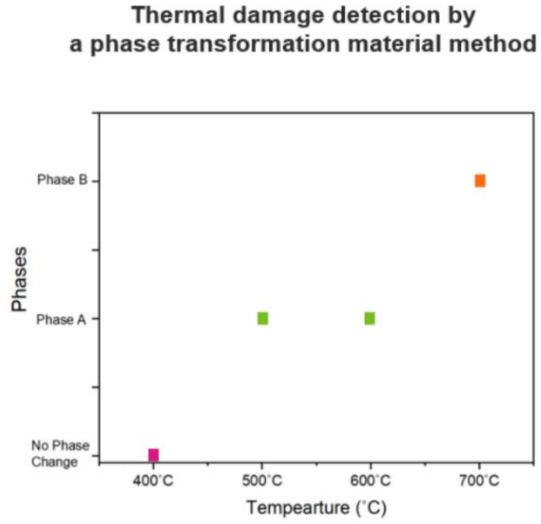


Fig. 6. Thermal damage detection method by phase transformation material.

III. Conclusions

Multi-cycle carrier wafers were reused after LLO was demonstrated using specially deposited film layers. Process conditions were optimized to enable release of the developed films, and an additional upper sacrificial layer on the top carrier wafer helped limit topological damage. This enabled multiple separation and rework cycles. Thermal characterization of the device layer after LLO showed no phase changes around 400 °C. Currently, lower-temperature thermal detection methods are being developed to prevent heat generated during laser ablation from damaging the device layer.

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