

Laser Scribing of Copper/Low-k Dielectric Semiconductor Materials by Nanosecond and Ultrafast Pulseswidth Lasers

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Abstract

The adoption of copper/low-k technology into semiconductor devices has created new challenges for mechanical dicing. Low-k dielectrics are less mechanically strong compared to SiO₂, making these layers susceptible to chipping, cracking, and delamination during saw dicing. Laser scribing or dicing of these devices offers a possible solution. Because the absorption of laser energy is dependent on the materials and layer thicknesses in a semiconductor stack, careful selection of the laser parameters are important for laser processing. This presentation provides a comparison of laser processing of copper/Black Diamond low-k materials using nanosecond and ultrafast pulseswidth lasers.

Keywords: wafer scribing, wafer dicing, laser singulation, laser micromachining

Introduction

The challenges of dicing semiconductor device wafers are increasing as new materials are adopted and as die streets shrink. The established method for dicing is by mechanical saw. However, the adoption of Cu/low-k dielectric materials has made the saw process slower and/or more difficult due to the susceptibility of these materials to chip, crack, and delaminate [1,2]. These challenges make laser scribing prior to saw dicing an attractive solution. Laser scribing involves using the laser to clear the dicing street of the semiconductor device layers down to the Si substrate [3]. This is typically done either by cutting a single wide scribe (wider than the saw blade) down the middle of the dicing street, or by cutting two narrow scribes along both outer edges of the dicing street to sever structures in the dicing street from the interior of the device [4, 5]. This process is followed by mechanical saw dicing either inside or between the laser scribe(s).

A key advantage of laser processing is speed. However, the maximum possible laser scribing speed can be slower than desired depending on the types and variety of structures in the dicing street. Structures such as probe pads, alignment marks, test patterns, etc, can pose a challenge for the laser depending on the material composition and thickness. This can result in localized area of chipping and delamination at high scribing velocities. A better

understanding of how different lasers and laser parameters interact with structures in the dicing streets of real devices is desired, so an efficient method for selecting the best laser and laser parameters to process any device can be established.

Ultraviolet wavelength (UV) lasers (e.g. 355 nm) are prime candidates for laser scribing because UV light is more readily absorbed by dielectric materials compared to infrared (IR) (e.g. 1064 nm) lasers [6]. "Ultrafast" wavelength lasers (≤ 10 ps) are also candidates for laser scribing because they allow for non-thermal absorption processes and also produce a smaller heat affected zone around the processed area [7, 8, 9]. This manuscript will compare laser scribes made by typical nanosecond pulseswidth lasers with ultrafast lasers. For the first part of the study, an IR femtosecond pulseswidth laser is compared to both a picosecond and nanosecond pulseswidth UV lasers for scribing blanket films of Black Diamond 1 (BD1) and Black Diamond 2 (BD2). For the second part of the study, a Cu/BD1 test wafer is processed using a square spatial shaped beam with nanosecond and picosecond UV lasers.

Experimental

Table 1a shows the specifications for the lasers used in the scribing study. Both shaped and unshaped laser spot profiles were used. Gaussian shape means that the spot is round with a Gaussian

shaped spatial energy density profile. The Top Hat shape is round with a near-uniform spatial energy density profile. The Square shape is square with a near-uniform spatial energy density profile.

Table 1. Lasers used in the study

Laser ID	Spot shape	Pulse-width	1/e ² spot size	λ (nm)	Rep rate (kHz)
fslR	Gaussian	570 fs	10 μm	1064	100
psUVg	Gaussian	10 ps	20 μm	355	200
nsUVt-1	Tophat	30 ns	50 μm	355	70
nsUVg-1	Gaussian	30 ns	10 μm	355	70
psUVs	Square	10 ps	40 μm	355	200
nsUVs	Square	23 ns	49 μm	355	20
nsUVt	Tophat	23 ns	32 μm	355	20

The BD1/BD2 blanket wafers and Cu/BD1 test structure were purchased from Silyb Wafer Services, Inc (part numbers 812CEBA, BDIIx, and s854CUBDSION). The BD1 and BD2 blanket films were 1 μm and 500 nm thick respectively on silicon substrates. The Cu/BD1 test structure uses the commercially available “MIT-854” layout that contains a wide range of test structures with a range of line widths and pitch. The s854CUBDSION wafer underwent CMP to resolve the Cu lines a few days before laser processing, and the resulting structures were unpassivated Cu lines as shown in Figure 1a & 1b.

When comparing scribe results using the various lasers, the properties of laser fluence and linear dose were employed. The laser fluence was calculated from:

$$\text{Fluence} = \frac{\text{Pulse Energy}}{\text{Spot Area}}$$

The linear dose was calculated from:

$$\text{Linear Dose} = \frac{\text{Spot size}}{\text{Bite size}} \times \text{Fluence}$$

and

$$\text{Bite Size} = \frac{\text{Scan velocity}}{\text{Rep Rate}}$$

Optical constants for the Black Diamond films were measured using a JA Woollam VASE spectroscopic ellipsometer. Measurements were made at 60, 70, and 80° angles of incidence and wavelengths of 300 to 1700 nm.

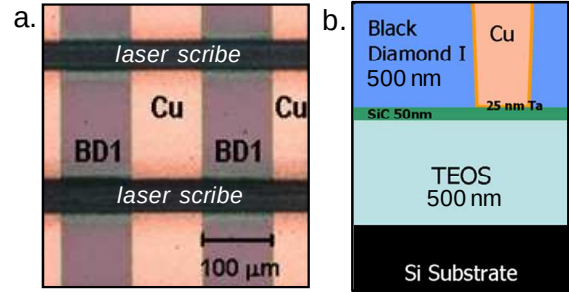


Figure 1. Patterned test structure used in the laser scribing in the study. Fig. 1a shows the top-down microscope image of 100 μm wide Cu and Black Diamond 1 patterns in the MIT-854 test wafer. Fig. 1b is the cross-section of the device

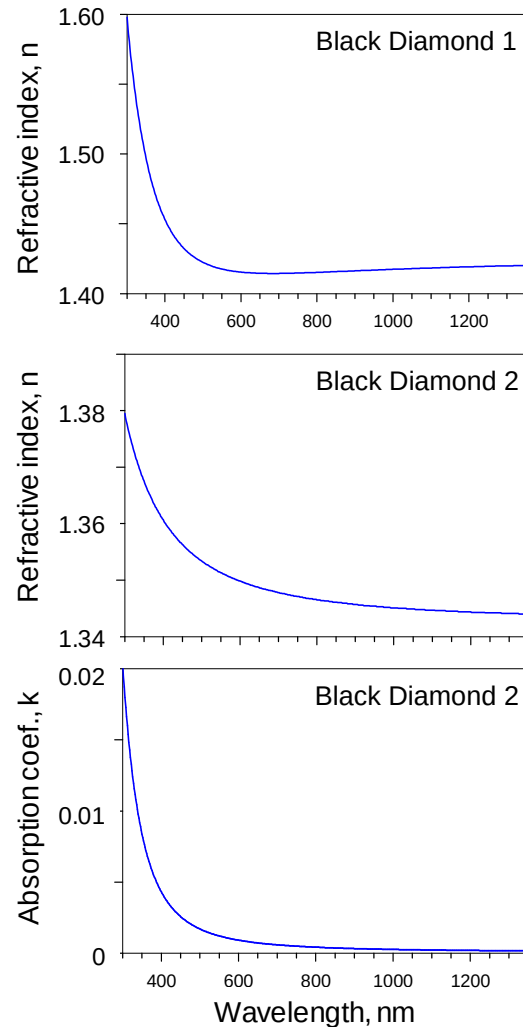


Figure 2. Wavelength dependent optical constants for BD1 and BD2 measured by ellipsometry. The absorption coefficient for BD1 was determined to be zero (<0.0001) for the wavelength region of 300 to 1350 nm.

Results and Discussion

Part 1 – Low-K Scribing of BD1 and BD2

Black Diamond is Applied Material's trade name for their low-k dielectric PE-CVD carbon-doped silicon dioxide materials. According to the Applied Materials website, the BD2 material undergoes a UV cure to "induce porosity and strengthen the Si-O backbone". The blanket materials were analyzed by spectroscopic ellipsometry, and the resulting optical constants are shown in Figure 2. BD2 has a lower refractive index and a non-zero k-value in the range of interest compared to BD1. At 355 nm BD1 and BD2 had $[n, k]$ values of $[1.490, 0.000]$ and $[1.367, 0.008]$ respectively.

Figure 3 shows SEM cross-section images for scribing 1 μm thick BD1 on Si using a fs IR, ps UV, and ns UV lasers (fsIR, psUVg, and nsUVt-1). The SEM images shown are for the lowest linear dose and fluence combination required to scribe the material down to the underlying Si. All 3 laser types scribed

the BD1 material cleanly without any significant chipping, splash, or cratering. In Fig. 3 the minimum linear dose of laser energy to scribe through the 1 μm thick BD1 layer is compared for each case. The ps UV laser required the lowest linear dose of 1.6 J/cm^2 . The femtosecond IR laser required a slightly larger linear dose of 2.0 J/cm^2 , perhaps because IR light is more transparent to the BD1 material compared to the ps UV. The 30 ns pulsewidth UV laser required a much higher linear dose of 9.5 J/cm^2 by comparison. These results suggest that the increased absorption from non-thermal effects provided by the ultrafast pulsewidths helps to reduce the required linear dose.

The cross-section SEM images for the 500 nm thick BD2 film processed by the same 3 lasers are shown in Figure 4. The minimum linear dose to scribe the BD2 material was comparable to the BD1 results for the three laser types. For the ns UV laser, the cut was splashier compared to the other lasers, and also the BD1 results. This difference may be due to the lower mechanical strength of the BD2 material, combined with the larger heat affected zone created by the longer pulsewidth.

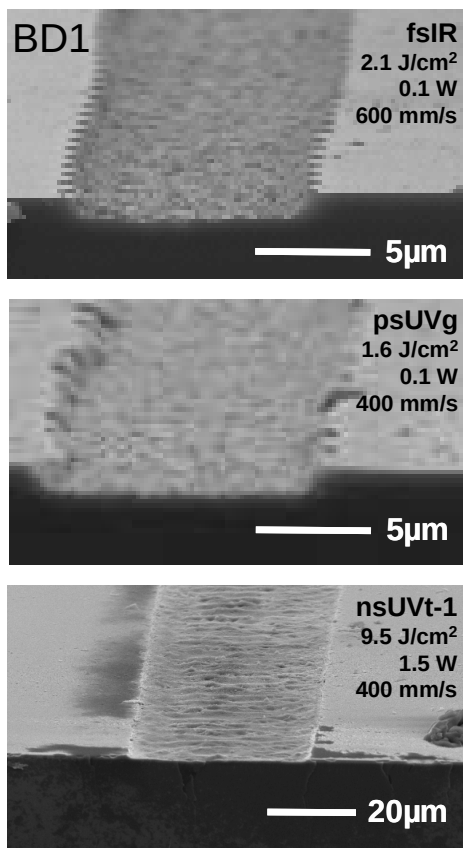


Figure 3. Comparison of BD1 1 μm thick blanket film on Si processed by ultrafast and nanosecond pulsewidth lasers.

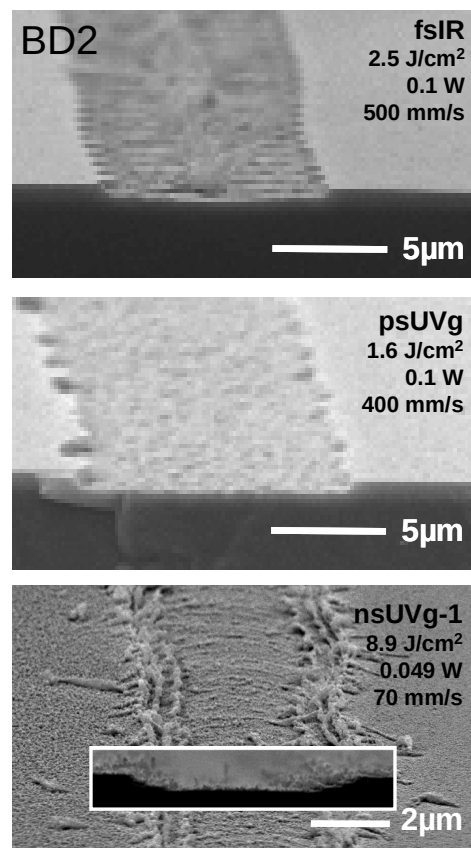


Figure 4. Comparison of BD2 1 μm thick blanket film on Si processed by ultrafast and nanosecond pulsewidth lasers.

Part 2A – Cu scribing in the Cu/BD1 test structure

A series of laser scribes were made in a Cu/BD1 test wafer using a wide range of powers and scribe velocities. An area of the test wafer containing 100 μm wide x 500 nm thick Cu lines separated by fields of BD1 was selected for the scribing studies (see Fig. 1a). The two lasers used were a 10 ps UV laser with a 40 μm square spot size (psUVs) and a 23 ns UV laser with a 49 μm square spot size (nsUVs). Figure 5 shows summary graphs of the results obtained for the laser scribes in Cu by the ps UV and ns UV lasers.

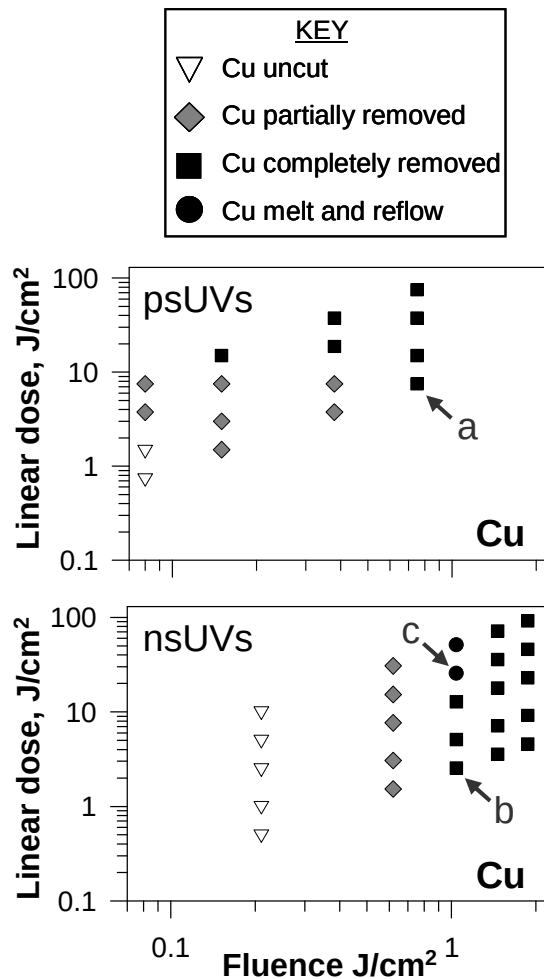


Figure 5. Results for scribing an unpassivated, 500 nm thick Cu line in a test wafer by ps and ns pulsedwidth lasers. Each point on the graph represents a laser scribe experiment. Labels “a” and “b” denote the lowest linear dose required to completely scribe the Cu line for the two lasers (7.5 J/cm² for picosecond, and 2.6 J/cm² for nanosecond). Label “c” denotes the laser parameters that resulted in Cu reflow.

Each point on the graphs represents an individual scribing experiment. In addition, the graph symbols indicate the process result for the scribe using a 3-point scale (∇ = Cu unaffected by the laser, $\diamond$ = Cu layer partially scribed, and $\blacksquare$ = Cu completely scribed). It is important to note that in the key “Cu layer completely removed” means that it was scribed down to the underlying TEOS (or SiC) layer, not to the Si substrate (refer to Fig. 1b).

A convenient method is desired to compare a single set of process results between the two graphs shown in Fig. 5. One method is to compare data points with the lowest combination of linear dose and fluence observed for the lasers to completely scribe the Cu layer. These points are denoted by “a” on the ps UV graph, and “b” on the ns UV graph for Cu. Figure 6 shows the comparison between these two points. Several observations can be made:

1. The ns UV laser required $\sim 1/3$ the linear dose to scribe the Cu compared to the picosecond laser, or 2.6 vs. 7.5 J/cm² respectively. In addition, the lowest linear dose required to initiate removal of the Cu was 1.5 J/cm² for both lasers. This suggests that the ns UV laser has a faster removal rate for Cu, rather than a lower ablation threshold.
2. The bottom of the scribe for the ps UV laser has a regular grain-like structure and no splash as shown in Figure 7. The bottom of the ns scribe has a smoother melted appearance.

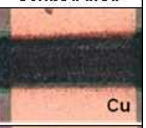
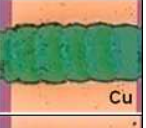
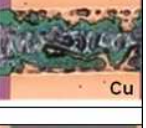
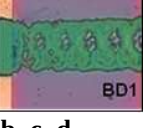
Graph point	Laser used	Scribe material	Power (W)	Scribe velocity (mm/s)	Linear dose (J/cm ²)	Microscope image of scribed area
Fig. 5 a	ps UVs	0.5 μm Cu	2.4	800	7.5	
Fig. 5 b	ns UVs	0.5 μm Cu	0.50	400	2.6	
Fig. 5 c	ns UVs	0.5 μm Cu	0.50	40	25.5	
Fig. 8 d	ps UVs	0.5 μm BD1	0.48	800	1.5	
Fig. 5 e	ns UVs	0.5 μm BD1	0.50	400	2.6	

Figure 6. Summary of results for points a, b, c, d, and e in the plots shown in Fig. 5 and Fig. 8.

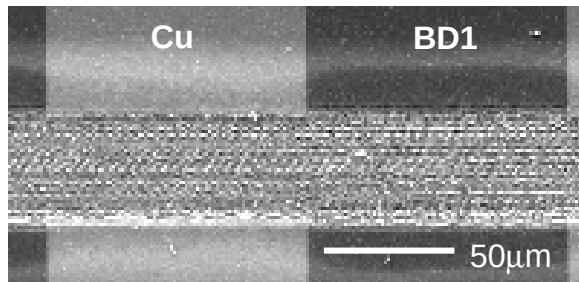


Figure 7. SEM image of scribe bottom for the psUVs laser scribe of Cu and BD1.

- It was observed that the Cu was not as cleanly removed at lower velocities, even if the laser fluence was significantly increased (denoted by “c” in Figs. 5 & 6). Closer inspection revealed that the incomplete metal removal is due to molten Cu that has reflowed into the scribe area and solidified. The onset of this effect begins with reflow confined along the edges of the Cu scribe, resulting in an unexpectedly narrow scribe. As the scribe velocity continues to decrease, Cu reflow was observed in the center of the scribed area as shown in Fig. 6.

Part 2B – BD1 scribing in the Cu/BD1 test structure

To evaluate BD1 layer scribing in the Cu/BD1 test wafer, the same convenient method of comparison that was used for Cu scribing is employed. Figure 8 shows a summary graph of the results for the laser scribes in BD1. In Fig. 8, label “d” and “e” denote the lowest combined linear dose and fluence required to completely scribe the BD1 area for the two lasers. Fig. 6 shows the comparison between these two points, and several observations can be made:

- The ns UV laser required slightly higher linear dose to scribe the BD1 compared to the picosecond, or 2.6 vs. 1.5 J/cm² respectively.
- The ns UV laser required the same minimum linear dose of 2.6 J/cm² to scribe both the Cu and BD1. In addition, comparison of the ns UV graphs in Figs. 5 and 8 reveals that the Cu and BD1 process graphs are fairly similar (much more similar than comparing the Cu and BD1 process graphs for the ps UV). These two observations suggest that the ns UV laser is actually less sensitive to the material being processed compared to the ps UV laser.
- The ps UV laser required only 1.5 J/cm² to scribe the BD1, compared to 7.5 J/cm² for the Cu. In addition, the lowest linear dose

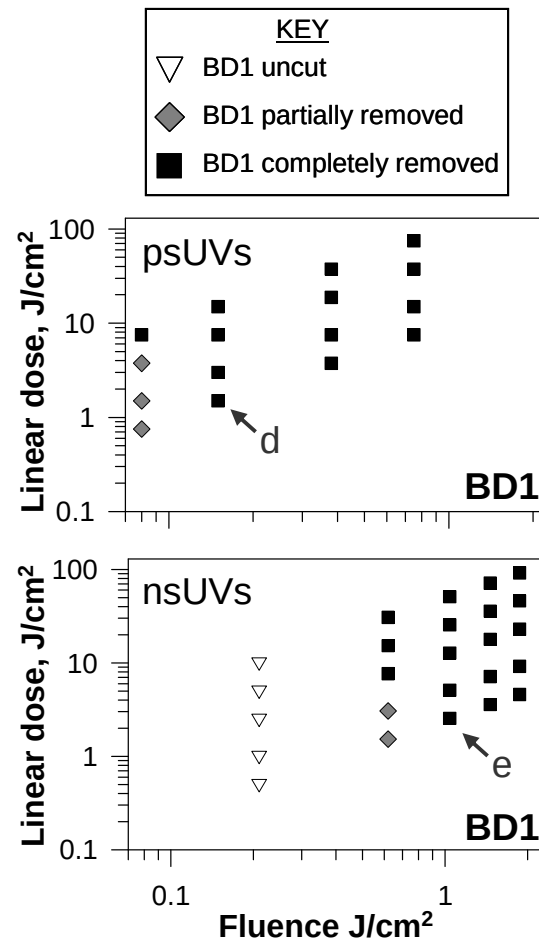


Figure 8. Results for scribing a 500 nm thick BD1 layer in a test wafer by ps and ns pulsewidth lasers. Each point on the graph represents a laser scribe experiment. Label “d” and “e” denote the lowest linear dose required to completely scribe the BD1 line for the two lasers (1.5 J/cm² for picosecond, and 2.6 J/cm² for nanosecond).

required to initiate removal of the BD1 by the ps UV laser was 0.75 J/cm². This suggests that the ps UV laser has both a lower ablation threshold and a significantly faster removal rate for BD1 compared to Cu.

- The 1.5 J/cm² dose required by the picosecond laser to remove the BD1 in the test structure is on par with the results obtained for the BD1 blanket wafer in Part 1 (1.6 J/cm²). However, the nanosecond laser required only 2.6 J/cm² to scribe BD1 area on the test wafer compared to 9.5 J/cm² to scribe the BD1 blanket wafer. This demonstrates the problem when scribing semiconductor materials and why laser & laser parameter selection is important. The composition and thickness of layered media

can affect the optical absorption of materials [10]. Other physical properties of the materials can also play a role in the scribing efficiency, such as differences in thermal conductivities between, coefficients of thermal expansion, etc.

Part 2C – Scribing of TEOS layer under the Cu/BD1

The Cu/BD1 test wafer had a 500 nm thick TEOS layer under the Cu and BD layers that also must be removed to complete the scribing process. Evaluation of the data sets in Part 2A and 2B revealed evidence of chipping at some data points in the underlying 500 μm thick TEOS (SiO_2) layer. SEM images are shown in Figure 9. For the ns UV laser (nsUVt) Fig. 9a and 9b reveals that the primary removal mechanism of the TEOS is cracking, chipping and flaking caused by melting or ablation of the underlying silicon. For the ps UV laser (psUVs) shown in Fig. 9c, inspection of the ps UV scribe edges reveal extensive chipping in the TEOS only under the BD1 regions of the test device. Closer inspection reveals that the overlying Cu line adjacent to the scribe is preventing the chipping in these areas. This kind of material removal process is not desirable for laser scribing, and future investigations will determine what the optimal laser parameters should be to more effectively scribe the TEOS layer.

Conclusions

Laser scribing offers a way to increase the speed of wafer dicing by removing or severing the delicate semiconductor device layers prior to mechanical saw dicing. However, some combinations of semiconductor device materials, composition, and layer thickness can limit the maximum speed of the laser scribing process. This manuscript begins the task of deconstructing these devices to understand what is the best laser (or laser parameters) for different kinds of semiconductor device wafers.

Based on the process conditions used in this study, a few generalizations can be made (for the sake of brevity, the term “more efficient” will be used to indicate a situation where a lower combination of laser linear dose & fluence could be used to scribe a material). First, the ns UV laser was more efficient at scribing Cu compared to the ps UV laser, while the ps UV laser was slightly more efficient for scribing BD1 layers than the ns UV laser. Second, the ns UV laser was much more efficient at scribing BD1 when it was built into the Cu/BD1 test structure, compared to a blanket film of BD1 on Si suggesting an environmental dependence. On the

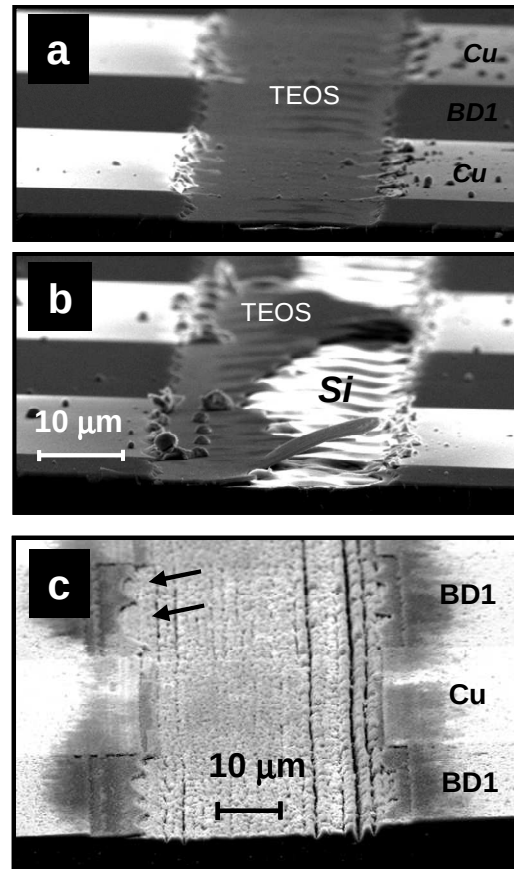


Figure 9. Results for processing the 500 nm thick TEOS layer that was underneath the Cu and BD1 lines. 9a & b shows the exposed TEOS layer before and after processing by a ns UV laser (nsUVt). 9c shows the result after scribing the TEOS layer by the ps UV laser (psUVs).

other hand, the ps UV laser was not sensitive to the environment of the BD1 material, and had the same efficiency to process it either on the blanket wafer or in the Cu/BD1 device. Third, when scribing the Cu/BD1 test device, the ns UV scribed both Cu and BD1 with equal efficiency. On the other hand, the ps UV laser was much more efficient at scribing BD1 compared to Cu. This suggests the ns UV laser is not “material sensitive” for scribing the Cu/BD1 device, while the ps UV laser is. Forth, Cu reflow was observed for low-velocity scribing with the ns UV laser, while no reflow was observed for the ps UV laser. Finally, neither the ps or ns UV laser was able to scribe the TEOS interlayer in the Cu/BD1 device without chipping.

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