

Article

Imaging Techniques for 3-Dimensional, Non-Line-of-Sight Structures Fabricated in Silicon Carbide

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Abstract: Advances in silicon carbide fabrication techniques enable the fabrication of high aspect ratio non-line-of-sight structures. The further development of non-line-of-sight fabrication tools and the use of the non-line-of-sight structures requires a set of measurement techniques. The goals of the measurement techniques are to (1) quickly detect the success of the fabrication and determine when a failure occurs, (2) accurately measure the shape of the subsurface structure, and (3) accurately characterize the structure. The first goal is attained using subsurface optical microscopy and single point confocal microscopy with a demonstrated resolution of 3 μm . The second goal is attained using X-ray computer tomography with a resolution of 500 nm. The third goal requires the accuracy of scanning electron microscopy. The substructures are brought to the surface through focused ion beam milling if the structures are less than 30 μm deep and through ablation cleaving and polishing for deeper substructures.

Keywords: silicon carbide; microfabrication; non-line-of-sight imaging



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1. Introduction

Advances in fabrication enable the production of non-line-of-sight (NLOS) structures. Examples of NLOS structures include 3D integrated circuits [1–3], photonic crystals [4–6], metamaterials [7–9], additive manufacturing [10,11], a high aspect ratio through silicon vias [12–15], etc. There is a need for a quick and accurate metrology for these NLOS structures. The structures that are fabricated in a layer-by-layer approach are more amenable to existing metrology methods, such as optical microscopy, scanning electron microscopy, atomic force microscopy, etc. However, there is a need to image substructures. Several subsurface imaging techniques have been explored in these different applications, including THz imaging [16,17], X-ray computed tomography (CT) [18–23], chemiluminescence, scanning white light interferometry [24], and confocal laser holographic microscopy [25].

A recent advance in SiC fabrication creates NLOS structures with high aspect ratios [15]. This new SiC fabrication technology has the potential to create novel three-dimensional through-wafer interconnects and micro-scale heat exchangers. However, the development of this technique has been hampered by the technically difficult imaging and characterization of these very high aspect ratio (>100:1) and NLOS structures. The difficulties associated with the metrology of NLOS structures are exacerbated when the aspect ratio increases because the required imaging resolution increases, and it is more difficult to localize the structures.

There are three main functions that need to be met by the metrology technology for the SiC high aspect ratio NLOS structures to facilitate the further development of the

method presented in [15]. (1) The fabrication method requires the collocation of electron holes and hydrofluoric acid. The metrology needs to quickly detect when the etching stops. (2) The electron holes are created through a nonlinear process (two photon absorption). Therefore, there is a need for metrology technology to accurately measure the shape of the subsurface structure. (3) The subsurface structure needs to be characterized, including surface roughness, the aspect ratio, the via diameter, etc.

2. Materials and Methods

All of the subsurface microstructures are fabricated in single crystal n-type 4H-SiC using the fabrication technique described in [15]. It is challenging to characterize the subsurface microstructures as there is usually only an entrance and exit hole visible.

Five measurement techniques are used to characterize the subsurface structures. These techniques are grouped according to the measurement source.

2.1. Optical Measurement Techniques

2.1.1. Subsurface Optical Imaging

The first and most obvious technique for verifying subsurface features is subsurface optical microscope imaging. In this technique, the sample is placed in an optical microscope and the focal plane of the microscope moves inside of the bulk of the substrate. Because SiC is transparent to visible light, an optical microscope can focus on any subsurface feature that has a component that is parallel to the top surface. This imaging can be performed post-process or with an in situ microscope during the process. No damage to the substrate or the microstructure is needed for viewing, and it has the capacity to image large substrate features. Figure 1a is a diagram showing subsurface optical imaging where the focal plane of the objective is past the front surface and focuses on the NLOS undercut microchannel. Figure 1b is an optical microscope image of the surface of the SiC above the microchannel, and Figure 1c is the subsurface optical microscope image of the microchannel approximately 125 μm below the surface. The microscope used in this work is a Zeta-20 Optical Profiler.

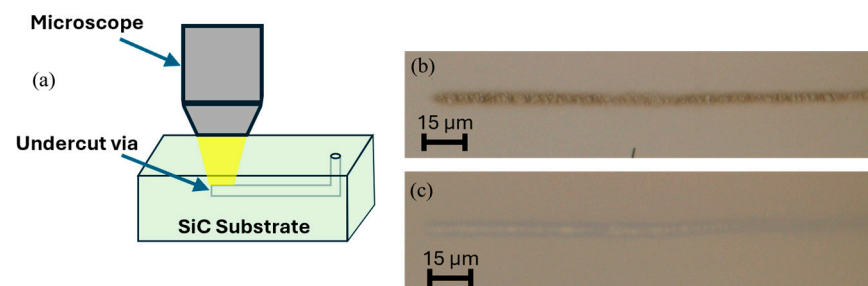


Figure 1. (a) Diagram of optical subsurface imaging. (b) Optical image of the top surface of the wafer above an NLOS via. (c) Image of the NLOS via under the surface.

This technique is capable of quickly verifying that a subsurface feature is present, but only if it has a component parallel to the surface. With the microscope integrated into the fabrication equipment, a scan can be performed periodically to ensure that the etching has not stopped. A limitation of this technique is that it only shows a 2D projection of the underlying microstructure. It also does not do much to determine the quality of the microchannel in terms of inner diameter, wall roughness, etc. It is the simplest form of NLOS structure verification.

2.1.2. In Situ Single-Pixel Confocal Reflectance Microscope

The next technique for quick verification of subsurface features is confocal reflectance microscopy. This method relies on precise alignment of a pinhole aperture to provide

axial resolution. Figure 2 shows a diagram of a single-pixel confocal reflection microscope. Excitation light from a laser focuses down to a small point through an objective lens into the bulk SiC substrate. Due to the change in index of refraction [26], some of the light reflects into the objective lens and exits as collimated light. The reflected light is directed by a beam splitter through a lens that focuses it through a pinhole. The pinhole is aligned to the focal length of the lens so that all collimated light that enters the lens passes through the pinhole and onto a photodiode optical power meter. Out-of-focus light (such as light reflected off of the front surface) is blocked by the pinhole. Only light that is reflected at the focal spot of the objective is detected, allowing for axial resolution. To create a 3-dimensional confocal scan, the sample is placed on a 3-axis translation stage and raster-scanned throughout the substrate to find all of the interfacial locations. This technique is useful in quickly verifying NLOS features in SiC, and it provides a non-destructive characterization of the diameter and depth. Because it provides axial resolution, it can also be used to accomplish metrology goal (2), measuring the shape of the subsurface features.

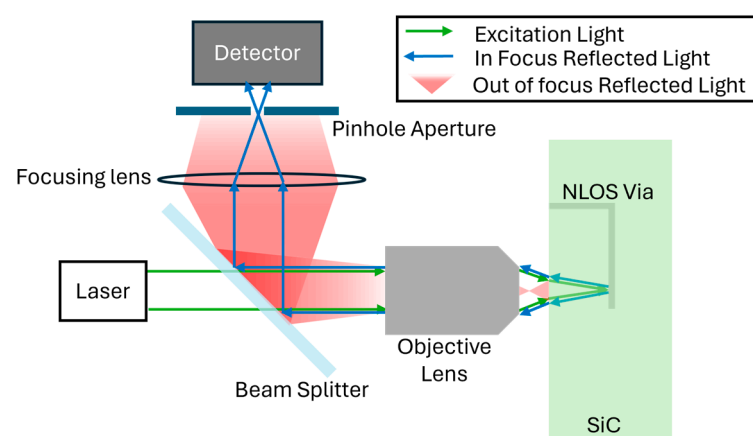


Figure 2. In situ single-pixel confocal reflectance microscope.

2.2. Scanning Electron Microscopy

Scanning electron microscopy (SEM) is a standard metrology tool with high accuracy [27]. However, it is only used to measure surface features. The key to using the SEM to image substructures is through cross-sectioning.

2.2.1. Focused Ion Beam with SEM

The first cross-sectioning method is performed using a focused ion beam (FIB). The equipment used to perform this imaging is an FEI Helios NanoLab 600 DualBeam FIB/SEM. It is equipped with an Elstar ultra high resolution (UHR) immersion lens field emission SEM (FESEM) column, which is capable of a resolution better than 1 nm. The SEM has an accelerating voltage range of 350 V–30 kV. The FIB uses a Tomahawk ion column with an accelerating voltage range of 0.5–30 kV and a probe current of 0.1 pA–65 nA. The FIB cut resolution can be as high as 2.5 nm. This equipment enables SEM imaging of the entrance hole and then precise milling using a gallium ion beam. The precision of the milling comes with the deficiency of a slow milling rate. The milling rate depends on the imaging resolution and the milling depth; in this work, the milling rate is 80 nm/minute; however, with deeper and deeper FIB cuts, the amount of milling needed goes up substantially, as more and more material needs to be cleared for an adequate viewing channel of the cross-section. This means that the milling time goes up exponentially with feature depth. Therefore, the features need to be less than approximately 30 μm below the surface for reasonable milling times (10s of hours). This limits the efficacy of this technique, as many of the subsurface structures are deeper than 30 μm . For low-depth experiments, this technique

works to create a precise and accurate cross-sectional cut for easy characterization of the critical dimensions of the NLOS features.

2.2.2. Ablation Cleaving and Precision Polishing with SEM

The FIB milling rate is too slow to image structures deeper than about 30 μm . Therefore, SEM imaging of any structure that goes deeper than that requires a faster material removal process. The extremely hard [28,29], chemically inert [30] material in combination with the high aspect ratio nature of the subsurface microstructures make even destructive techniques difficult. The microchannels that need to be imaged have diameters on the order of a few micrometers. Therefore, material removal needs to be combined with an imaging method.

There are three steps to this metrology approach. First, the sample needs to be cleaved close to the via. The cleave needs to be approximately parallel to the via and within 100 μm . Next, polishing needs to be performed in a polish and check approach to ensure that the polishing is stopped when half of the via is exposed. Then, the sample can be imaged using an SEM.

A standard score and cleave process does not work for this application because the extremely hard SiC material does not cleave down crystal lattice planes and the precision requires a clean cut near the via. In this work, we use an ablation cleave process. In this process, a damage plane is created using laser ablation. Figure 3 shows that the system uses a laser coupled with a high-numerical-aperture objective lens. In addition, the laser system is coupled with an optical microscope to enable imaging of the surface. The microscope uses the same optical path as the laser. The main objective for laser focusing provides magnification for the microscope. The sampling mirror allows a small fraction of the laser light to be imaged by the microscope camera to enable the laser focal spot to be viewed relative to the image of the via entrance hole.

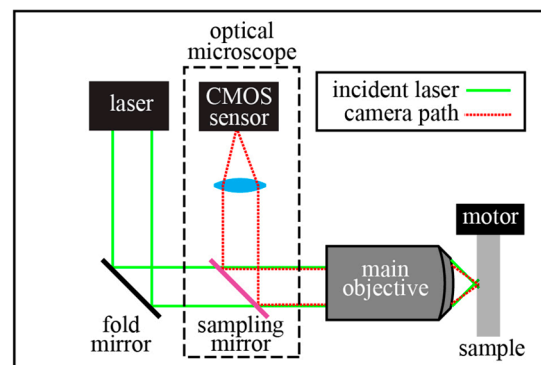


Figure 3. Diagram of the laser ablation system with an in situ optical microscope system.

Figure 3 is a diagram of the camera system showing its different components. The objective lens is a 50 $\times$ Mitutoyo long-working-distance objective with a numerical aperture of $\text{NA} = 0.55$. The objective serves to magnify the sample's surface to locate the NLOS via. It also serves to focus the laser light to an intense spot to facilitate ablation. The laser is a 5 W femtosecond laser with a 290 fs pulse width (Satsuma, Amplitude Laser Inc., Milpitas, CA, USA). The wavelength is 515 nm, and the maximum pulse energy is 9 μJ per pulse. The laser is set to a repetition rate of 250 kHz and a pulse energy of 3 μJ . The sample sits on a 3-axis stage, which carries the sample back and forth through the laser focus, creating a damage plane. Figure 4 is a microscope image of the top of a SiC wafer piece after the damage plane has been created, showing (a) before and (b) after cleaving the wafer. Figure 4b shows the separation of the two halves of the SiC piece and demonstrates the straightness of the cleave. These images were taken from a piece that was ablated with different laser parameters and objectives that made a bigger laser-affected area. The affected

area is 82 μm . The wafer is cleaved over a straight edge down the same line as the damage plane by applying consistent hand pressure firmly on either side of the ablation plane.

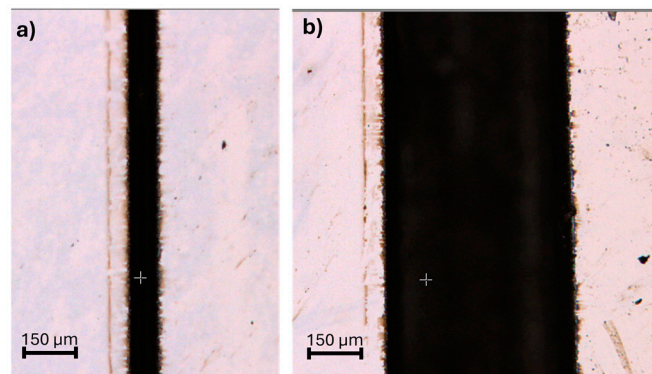


Figure 4. Optical microscope image of the damage plane (a) before cleaving and (b) after cleaving. (For this picture, a Thorlabs μ -spot 5 $\times$ objective and a Light Conversion Carbide Laser, with a wavelength of 515 nm and a pulse energy of 50 μJ /pulse, were used).

Once cleaved, the sample is placed in a mechanical edge polisher. The polisher is fitted with a 1 μm diamond grit pad. The process is time-consuming, as it is an iterative process of polishing and checking until the wafer is polished exactly halfway through the via. The small diameter of the vias makes this process difficult, and the yield can be low, but the sample can be imaged with an SEM to give superior image quality. This process has limitations, as it is a destructive process that can lead to ruined structures without the chance of imaging, but it also provides great insight into the via's size, feature depth throughout the wafer, surface quality inside of the wafer, and the shape of the structure.

2.3. X-Ray Measurement Technique

The most useful method for imaging 3D NLOS features in SiC is Micro-Computed Tomography (CT). Micro-CT scanning offers a non-destructive imaging technique capable of providing detailed 3D reconstructions of internal structures. It works using the same concepts as medical CT scans. X-rays are shot through the sample at many different angles and collected on the other side. The acquired 2D projections are reconstructed into 3D volumetric datasets using specialized software. The Zeiss Xradia Versa 620 microscope (ZEISS, Oberkochen, Germany) used in this work is capable of capturing submicron features at long working distances. It uses a dual-magnification technique that first uses geometric projection to magnify the sample. It then shines the magnified X-ray signal onto a scintillator that produces an optical image. That image is magnified using microscope optics before hitting a CCD. This allows for superior resolution at achievable working distances. As in other materials, the absorption of the X-rays differs in the bulk SiC and the air-filled microstructures. This difference is detected in sensors that capture the transmitted X-rays to form a 2D projection at a given angle.

Even though this technique is a non-destructive imaging method, the 2D projections require rotation of the sample. The rotation forces the sample to be small. The diameter of the sample needs to be less than 25 mm. Thus, a via in a wafer cannot be imaged unless the sample is diced into a small sample. CT X-ray imaging is categorized as a non-destructive imaging system; however, it is partially destructive, and the imaging time is long.

3. Results

3.1. Optical Measurement Techniques Results

3.1.1. Subsurface Optical Imaging Results

Figure 5 shows an example of subsurface optical imaging. The image of the top surface shows surface marring, which occurred during fabrication. Figure 5 also shows an optical microscope image focused down into the wafer. The vertical distance of the sample relative to the microscope objective is increased until the image comes into focus. This technique works through the entire 500 μm thick wafer.

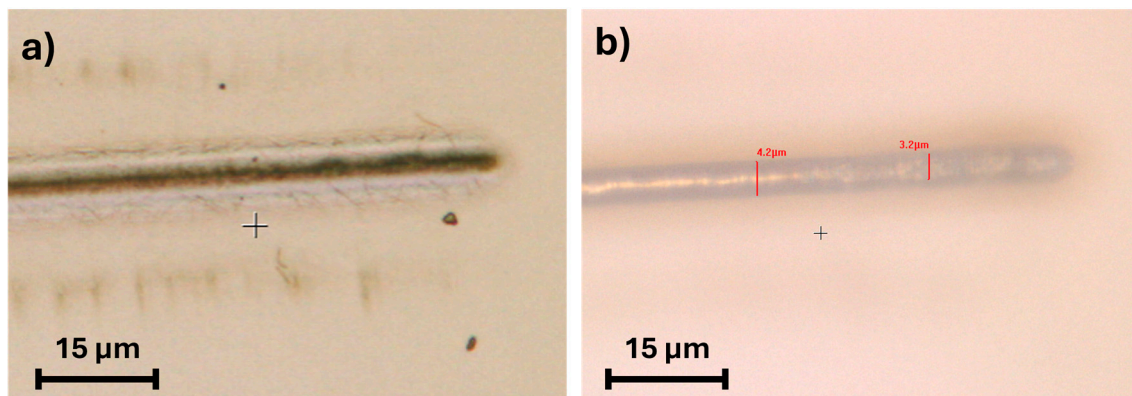


Figure 5. (a) Optical microscope image of the top surface above an NLOS undercut. (b) Optical microscope image focused down into the bulk of the SiC. The vertical shift in the sample is 6 μm .

Figure 6 shows a ray trace for a microscope objective with $\text{NA} = 0.55$ and a SiC substrate with a refractive index of $n = 2.68$ [26]. Notice that the refraction between the air and the SiC substrate results in a shift in the focal point. The refraction also results in aberrations, causing a blurring of the focus.

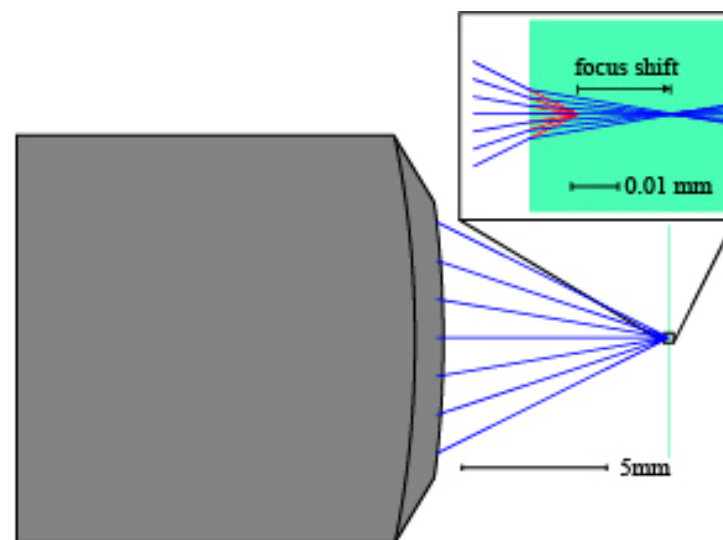


Figure 6. Optical ray trace from a microscope objective with $\text{NA} = 0.55$ and a SiC substrate modeled with a refractive index of $n = 2.68$. The red lines show the objective focal point without a SiC substrate.

Figure 7 shows the results of the ray trace analysis performed in Ansys Zemax OpticStudio (Canonsburg, PA, USA). Based on the ray trace analysis, the actual shift in the focus of the microscope is approximately three times larger than the physical shift of the sample relative to the microscope objective. The physical shift of the sample between the left and the right image in Figure 5 was measured to be 6 μm using the microscope stage encoder.

Based on the ray trace analysis, we can multiply the physical shift by the measured ratio of shift to obtain the actual depth of the substructure, which is 18 μm .

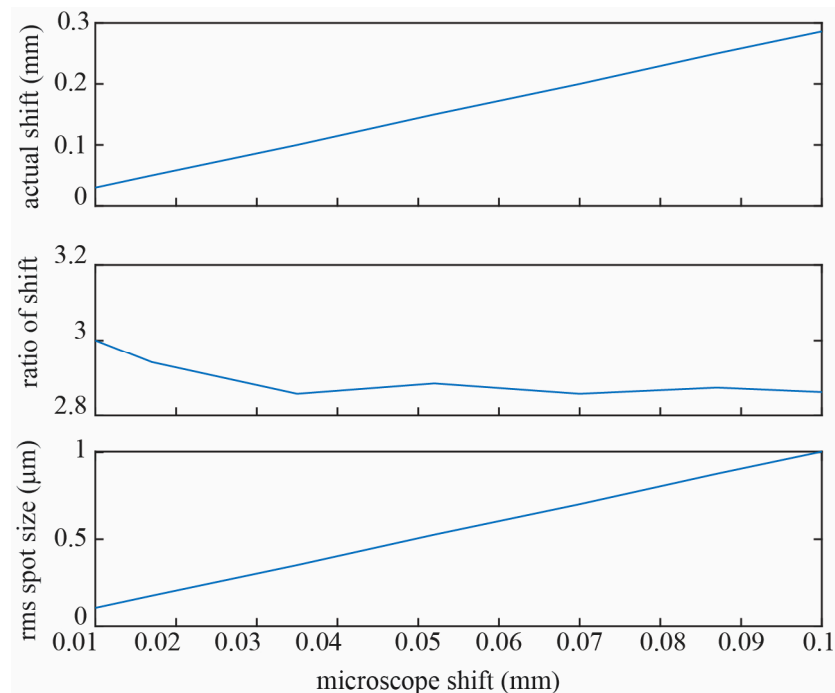


Figure 7. Ray tracing analysis of the effect of the SiC substrate on the focus of the optical microscope.

3.1.2. In Situ Single-Pixel Confocal Reflectance Microscope Results

Figure 8 shows a 3D scan of an undercut via in SiC. The single-pixel confocal reflectance microscope was scanned throughout the entire 3D NLOS etch, and the reflected power was captured. A threshold was adjusted to find the higher value points, which correspond to interfaces with significant changes in the index of refraction. The yellow plane at the top is the top surface of the wafer, where the reflection is most predictable. Figure 8a shows the raw data collected using the confocal sensor. The z-axis is the physical shift in focus. This axis is scaled by three in Figure 8b to obtain the actual depth of the undercut. The aberration stretches the subsurface undercut in the z-direction, limiting the axial resolution of this technique.

3.2. Scanning Electron Microscopy Results

3.2.1. Focused Ion Beam with SEM Results

Figure 9 shows a long undercut via that was imaged using the FIB and SEM technique. It shows the same NLOS via shown in Figure 5. Figure 9a shows an optical microscope image of a top-down view of this feature before being processed. The end of the via was FIB cut to reveal the NLOS structure. The acceleration voltage was 30 kV. No capping layer was added before SEM imaging. Figure 9b shows an SEM image of the top-down view of the same structure post-processing. Figure 9c is a cross-sectional view of the revealed end of the via, which is 18 microns below the surface. Figure 9d is a close-up SEM image. The large particles and much of the roughness in the via are due to the redeposition from the FIB cut process.

Figure 10 is an example of the FIB technique. It is an SEM image of several vias that were FIB cut to reveal cross-sectional views of the vias. The vias were filled with platinum to increase image contrast. They are 12 μm deep, and the processing time for these images was several hours.

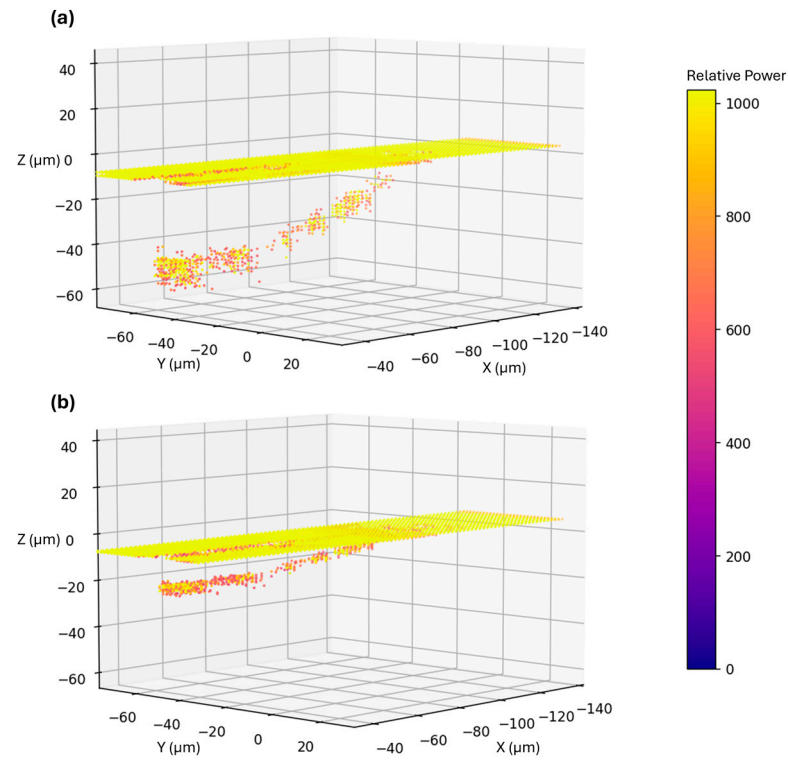


Figure 8. Confocal reflection scan of an NLOS undercut via. (a) is the raw data captured by the confocal sensor, and (b) is adjusted by $3\times$ in the z-axis to correct for the effects of spherical aberration. The yellow plane is the top surface of the SiC.

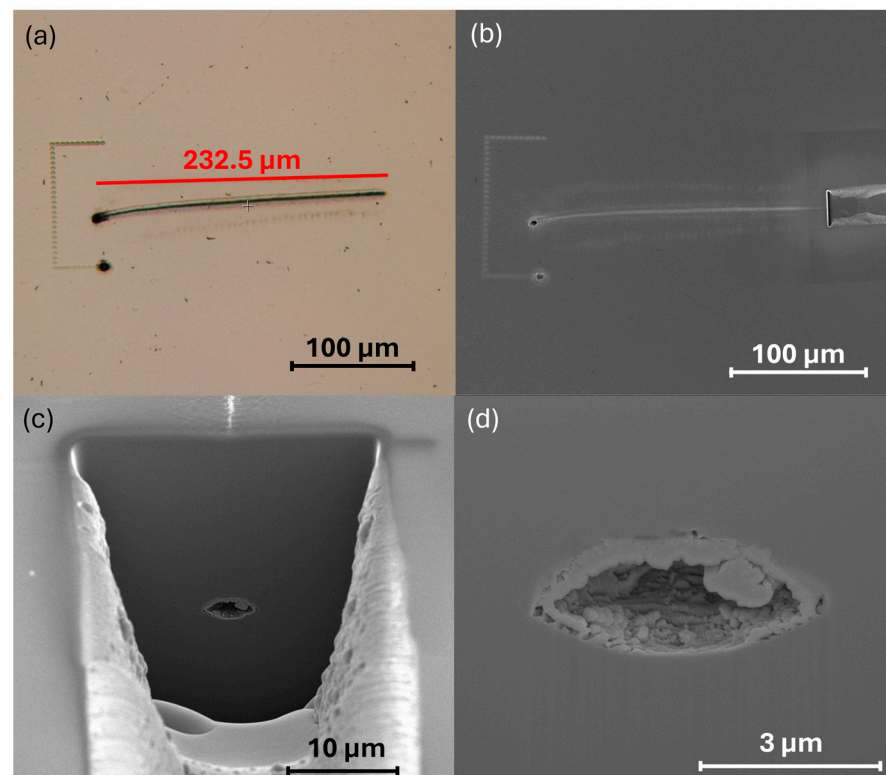


Figure 9. (a) Optical microscope image of the top surface of the same NLOS undercut via shown in Figure 5 prior to processing. (b) SEM image of the same NLOS undercut post FIB cut. (c) The cross-section view of the end of the undercut via that is revealed with the FIB cut. (d) Magnified SEM.

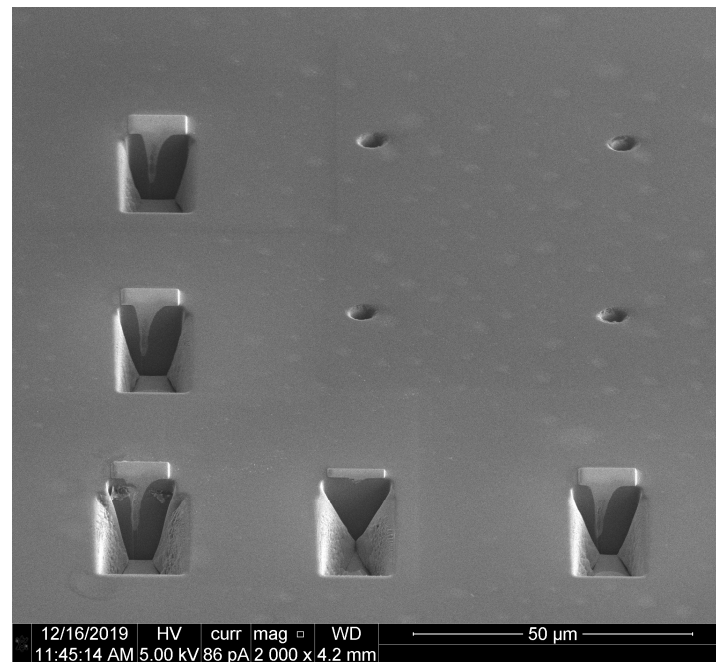


Figure 10. FIB-cut-processed via holes revealing a cross-section of small vias.

3.2.2. Ablation Cleaving and Precision Polishing with SEM Results

Figure 11a is an SEM image of a through-SiC via with an NLOS diagonal section within the bulk of the SiC. The cross-section was achieved using the process described above. The wafer is 350 μm thick, and the via varies in size from 9.24 μm near the top of the via to 2.51 μm at the bottom. This cross-section took around 5 h to create the damage plane for the cleave, and it took around 6 h to go through the polish and check iterative process. The images provide great resolution and insight into the quality of the via and its inner walls, as well as a clear picture of how the NLOS section looks. Figure 11b is another successfully imaged NLOS via in SiC that was achieved using the process described above. This via has a consistent diameter of 3–4.6 μm . There is a section in the middle of the via that appears to be a disconnect, but it is instead a section of the via that was outside of the polishing plane. This shows the limitation that for this technique to be effective, the etch must lie within the same plane.

3.3. X-Ray Measurement Technique Results

Figure 12a shows an image of the reconstructed X-ray scans taken using the Zeiss Xradia Versa 620 microscope. The 3D reconstruction shows an etch in the SiC of eight through-wafer vias that were performed in parallel. The vias are 8 μm in diameter, which is pushing the limits of the Xradia's resolution capabilities. The sample was downsized to a 5 $\times$ 5 mm² sample to help with increased resolution. Although this image is all in a single plane, this technique is not limited to a single plane. It can be used to image complex NLOS structures. This is an invaluable capability for more complex designs that are fabricated and imaged. This capability is illustrated in Figure 12b, which shows an etch that spirals as it moves through the thickness of the SiC wafer. The diameter of this via is about 2.3 μm . This is very close to the Xradia's maximum spatial resolution of 500 nm, making it difficult for even this tool to image these small subsurface features. The scan parameters for this scan were as follows: voltage of 40 kV, current of 75 μA , optical magnification of 19.878 $\times$, exposure time of 25 s per projection, 973 projections, and pixel size of 679 nm. All of these settings were chosen through trial and error to maximize clarity and resolution while maintaining a reasonable acquisition time. This sample was diced to

a 15 mm square sample to minimize the distance between the source, the sensor, and the sample to maximize spatial resolution.

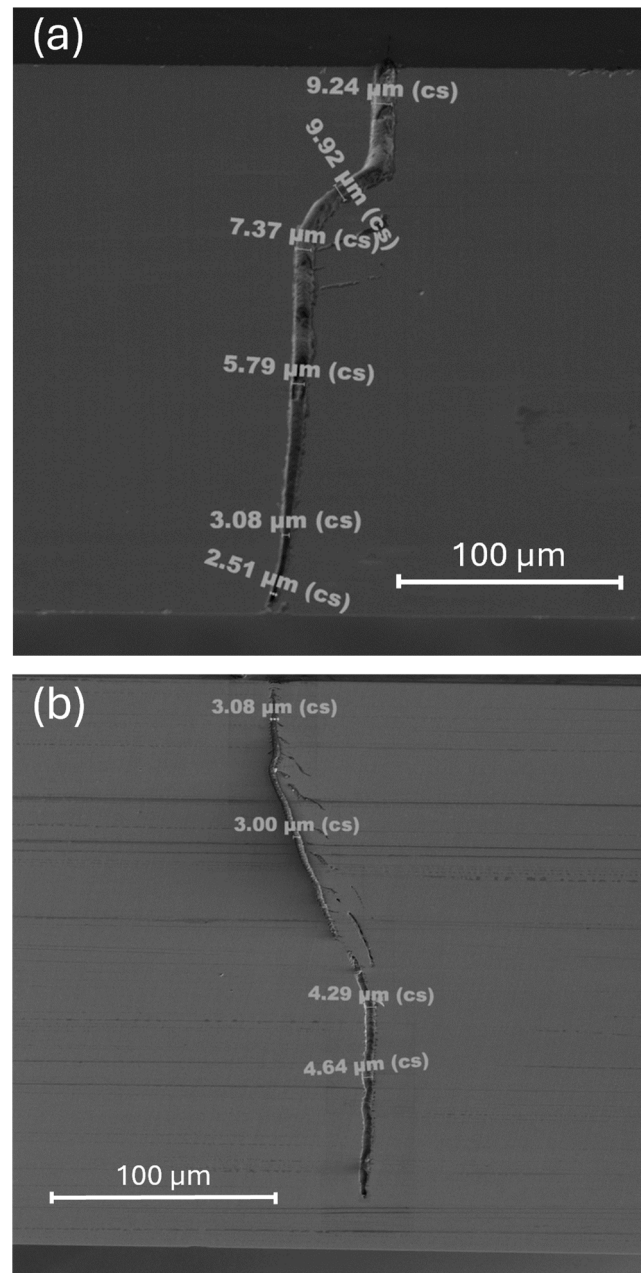


Figure 11. Cross-sectional SEM images achieved using the ablation cleave and polish technique of two different through-wafer vias with an NLOS turn in the middle. (a) depicts a via with varying diameters, and (b) depicts a via with a more consistent diameter, but it stops before going all of the way through the wafer.

Both CT reconstructions show the length and shape of the subsurface microstructures by contrasting the difference in X-ray transmission between the bulk SiC and the air-filled microchannels.

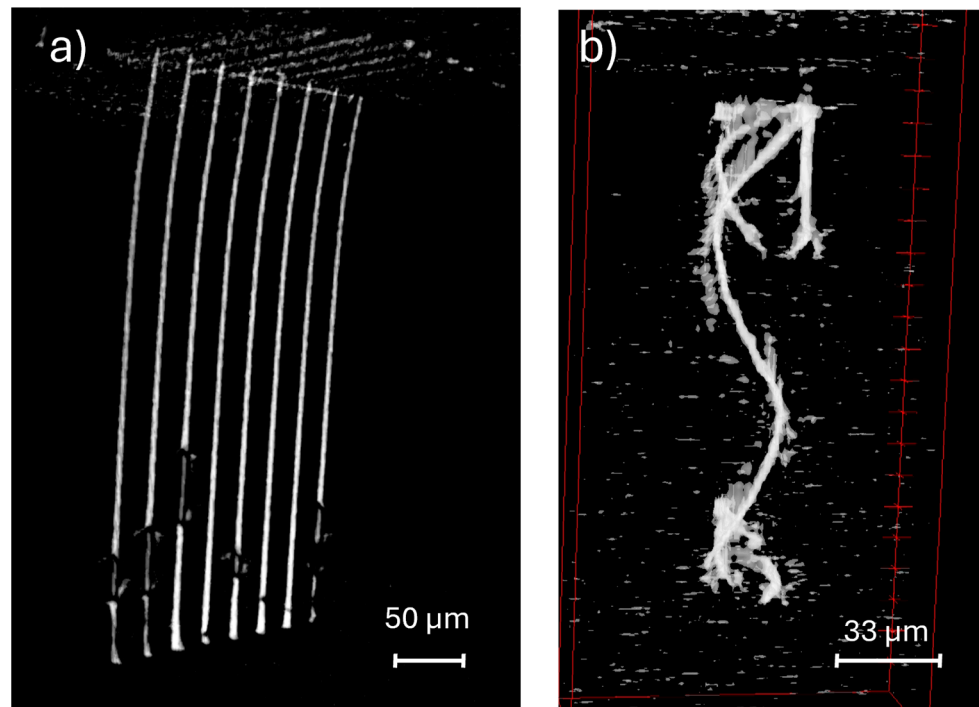


Figure 12. Micro-CT 3D reconstructions of (a) 8 vias that were fabricated in parallel and (b) an NLOS spiral via. Both are 3D reconstructions of etches made in SiC. The scans were performed using the Zeiss Xradia Versa 620 microscope.

4. Discussion

To make significant advancements in NLOS etching in SiC, the three objectives for the metrology system are to (1) quickly detect when the etching stops, (2) accurately measure the shape of the subsurface structure, and (3) accurately characterize the structure. Five metrology technologies are covered, including subsurface optical imaging, single-pixel confocal reflectance microscope, focused ion beam with SEM, ablation cleaving and precision polish with SEM, and micro-CT scanning. None of the imaging technologies meet all three metrology goals. However, all three goals can be attained with a combination of these metrology technologies.

The first goal is to find a quick, inexpensive way to determine a base level of experimental success. It is the first and most used form of verification. It is used after every NLOS experiment to verify if a structure is made, to give insight into the shape and depth of the structure, and to determine if a result warrants further investigation with other, more accurate methods. This is done using subsurface optical imaging and single-pixel confocal scanning. Subsurface optical imaging gives nearly instant feedback on whether the experiment is a failure or whether there is a subsurface feature that is worth further investigation.

Figure 5 shows that there is a subsurface microchannel. The optical resolution depends on the diffraction of the optical beam. The in situ microscope has a numerical aperture of $NA = 0.55$, resulting in an Airy disc-smoothing disc diameter of

$$D = \frac{(1.22)(\lambda)(n)}{NA} = \frac{(1.22)(0.55)(2.68)}{0.55} = 3 \mu\text{m} \quad (1)$$

Because the Airy disc diameter is greater than the rms spot (see Figure 7), the Airy disc determines the image resolution. With a channel size of around $3 \mu\text{m}$ (see Figure 11), the imaging resolution is on the order of the via diameter, resulting in a blurred image of the channel. The blurred image is sufficient for metrology goal (1), channel existence, but

insufficient for goal (3), channel characterization. The other limitation of optical imaging is that it is limited to seeing features that are parallel to the surface, as perpendicular features do not reflect light.

Figure 8 shows that single-pixel confocal scanning can also be used for quick verification. The confocal imaging uses the same laser and microscope objective as the optical microscope, resulting in a similar resolution. It is clear from Figure 8 that there is a subsurface feature detected by the confocal sensor, but the data are rather noisy. It is clear from the difference between (a) and (b) in Figure 8 that the data can be adjusted for a more accurate representation of the subsurface structure. The confocal microscope provides similar metrology to the optical microscope, but it is more amenable to system automation because it does not require image processing and can simply be integrated with thresholding.

The next metrology goal is to find a method for determining the shape of an NLOS microstructure. Confocal imaging can produce a measurement of the rough shape of the substructure. However, if a more accurate measurement of the shape is needed, the Zeiss Xradia Versa 620 micro-CT microscope is a better option. Figure 12 shows the capabilities of this technique, with two different experimental results. The eight vias are straight, but their aspect ratio is too high to image with other techniques. The spiral result shows that this technique is not limited to imaging a single 2D plane, which is essential for characterizing more complex subsurface microstructures. These two results serve as clear demonstrations of non-invasive imaging of NLOS structures in SiC. The resolution of this technique is only 500 nm. When the via diameters are 3 μm , there are only a few pixels that detect the via. This limitation makes it impossible to measure critical dimensions like inner-wall surface roughness, but, when used in combination with destructive techniques, they can be trusted to verify etch success. Etch parameters are honed using the other methods, and etch success is measured using micro-CT for devices that will not be destroyed for measurements. The micro-CT measurement technology achieves a better resolution than the optical microscope and the confocal microscope. It is also better for perpendicular structures. However, it is a time-consuming imaging process that requires small sample sizes. Thus, it does not meet metrology goal (1) to quickly detect when the etching stops, but it is better for metrology goal (2) to accurately measure the shape of the subsurface.

The final metrology goal is to characterize the critical dimensions of the NLOS structures, such as the diameter and shape of microchannels and the surface roughness of etched areas. This is an important step in fabrication development, as it requires the clearest, most accurate images. Not all experimental results should go through this step, as the methods tend to be more time-consuming and expensive. Because the methods used for this step also tend to be destructive, NLOS features intended for production are not brought through this step. The FIB cut with SEM and ablation cleave and polish with SEM are both very useful techniques for fulfilling the needs of this goal. They give a clearer picture of the substructure. The result in Figure 9 provide an example showing the information gained from the FIB cut. It shows that the cross-sectional shape of the microchannel is not perfectly circular, which is a characteristic not determined from Figure 5. The FIB cut technique is very precise, and it can be used for subsurface features relatively close to the surface, but it is very time-consuming, and it is not a viable option for deep NLOS etches. The ablation cleave and polish technique can be used for obtaining cross-sections of deeper NLOS structures. The SEM images in Figure 11 are examples of this technique's capability. The NLOS sections in the middle of the microchannels appear to be nearly parallel to the surface when using optical subsurface imaging because of the refractive effects of the SiC, but it is clear from the cross-sections that the turn is diagonal. This diagonal effect could have been detected using the FIB as well if the NLOS structure was close enough to the surface. Figure 11b shows where, unexpectedly, the etch stopped, which is nearly

impossible to image with optical subsurface imaging. The SEM also has great resolution and can measure very small features. By zooming in on the side walls of the FIB-cut or polished cross-sections, the surface roughness of the etch can be quantitatively measured. These techniques have limitations, including the processing time and the requirement that the etch be in a single plane, but they offer essential feedback for developing the fabrication technique.

5. Conclusions

This work demonstrates the approach to experimental, NLOS substructure characterization that is used in the development of a 3D SiC fabrication technique. The methods used in this work fulfill the metrology goals of quickly detecting when the etching stops, accurately measuring the shape of the subsurface structure, and accurately characterizing the structure. Optical subsurface imaging is a quick and easy way to verify that an NLOS structure exists. Destructive methods give great insight into the quality of the fabrication technique and measure the critical dimensions of the subsurface structures, but the sample is unusable after imaging. Micro-CT scanning does not have the same resolution that a direct SEM image provides, but it can characterize the success of useable samples. Micro-CT imaging is the most accurate non-destructive technique, but further development of the in situ single-pixel confocal microscope could prove to be a more useful technique for giving quick, inexpensive looks at the quality of an NLOS feature. There is no single method that fulfills all of the metrology goals for NLOS imaging, but the combination of these techniques is necessary to gain an accurate picture and to advance 3D NLOS fabrication capabilities in SiC.

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