Gallium nitride wafer slicing by a sub-nanosecond laser: effect of pulse energy and laser shot spacing

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Abstract: Gallium nitride (GaN)-based devices surpass the traditional silicon-based power devices in terms of higher breakdown voltage, faster-switching speed, higher thermal conductivity, and lower on-resistance. However, heteroepitaxial GaN growths like GaN on sapphire are not suitable for power devices due to the threading dislocation densities as high as $10^8/cm^2$. Recently, homoepitaxial GaN growth has become possible thanks to the native GaN substrates with dislocation densities in the order of $10^4/cm^2$ but the extremely high cost of the GaN substrates makes the homoepitaxy method unacceptable for industrial applications, and the slicing of wafers for reusing them is an effective solution for cost reduction. In this study, we will investigate a route for slicing the GaN single crystal substrate by controlling the laser pulse energy and changing the distance between each laser shot. The 2D and 3D crack propagations are observed by a multiphoton confocal microscope, and the cross-section of samples is observed by a scanning electron microscope (SEM). Results showed that two types of radial and lateral cracking occurred depending on the pulse energy and shot pitch, and controlling them was of importance for attaining a smooth GaN substrate slicing. Cross-section SEM images showed that at suitable pulse energy and distance, crack propagation could be controlled with respect to the irradiation plane.

Keywords: Gallium nitride (GaN); Laser slicing; Sub-nanosecond laser; Liquid crystal on silicon (LCOS)

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1. Introduction

Gallium nitride (GaN) is considered as a second most important semiconductor material, after silicon, because the global market of LED lighting is about to exceed 50 billion dollars. Characteristics like higher breakdown voltage, faster-switching speed, higher thermal conductivity, and lower on-resistance make GaN be a next-generation power semiconductor [1], and in some applications like power converters in electronic vehicles GaN plays a key role [2]. Historically, GaN is grown on foreign substrates like sapphire, silicon, or silicon carbide. Theses heteroepitaxially grown GaN films are suitable for LED or laser uses despite the threading dislocation densities as high as $10^8/cm^2$. However, in order to attain high-performance power devices dislocation density must be reduced orders of magnitude [3]. High-quality epitaxial GaN growth is now possible thanks to the native GaN substrates available in the market. The only disadvantage of these freestanding GaN substrates is their high cost for commercial applications. One efficient way to reduce the total process cost is to isolate the epitaxial device from the bulk GaN substrate and reuse it. Several lift-off methods such as growth over patterned masks [4–7], natural stress-induced separation [8,9], controlled spalling [10], chemical etching of sacrificial layers [11–15], substrate removal by grinding/etching [16–18], the use of weakly bonded detach layers like graphene [19], and laser lift-off [20] are reported for separating GaN films from the foreign substrates. Separating GaN film from a GaN substrate is also reported by using various techniques like chemical lift-off process [21], creating porous release layers via chemical etching or dry etching [22,23], controlled spalling [24], laser lift-off with an InGaN sacrificial layer [25], and ion implantation [26–29].

Most of above-mentioned methods for separating GaN film from the substrate require a complicated and time-consuming process and/or a large number of unintentional defects are usually induced during the separation process. Voronenkov *et al*. have recently demonstrated interesting results based on laser slicing lift-off of an epitaxial structure from a bulk GaN substrate using a femtosecond laser [30]. Tightly focused laser pulses can induce a local interaction between laser and wide bandgap semiconductors. The interaction of laser pulses with transparent materials is a powerful tool for the modification of material properties resulting in the formation of microvoids, metallization, and phase transformations [31]. GaN is a brittle wide bandgap semiconductor, which is transparent in a wide range of light spectrum from infrared (IR) to ultraviolet (UV). The laser ablation in these wavelength ranges is achieved via a non-linear effect involving multiphoton ionization. Upon laser irradiation, seed free electrons generate. These seed electrons further absorb the laser energy which can produce secondary electrons in collisions with neutral atoms of the GaN, generating electron avalanche. As a result, a significant change of optical response of the laser-irradiated region occurs and in the case of GaN it proceeds towards metallization, i.e., generating metallic gallium in the irradiation zone [32]. In this manner, the laser can be applied for slicing the GaN substrate by focusing the laser to the desired thickness. Several studies have reported slicing transparent materials such as sapphire, silicon carbide, and glass. Very few studies are also available in the literature regarding the cleaving of GaN substrates by laser irradiation [30,33–36]. However, a systematic study based on the effect of laser pulse energy, laser shot pitch on the crack propagation is lacking in order to achieve a smooth slicing surface, which does not require flattening process for further device fabrication.

2. Experimental procedure

In this study, a transparent single crystal c-plane GaN substrate with a thickness of 410 μm and dislocation density of 4.9×10^{6} cm^{-2} is subjected to a 532 nm green laser irradiation. The underlying idea is to focus the laser shots to an arbitrary depth, and propagate the cracks in the fracture plane with a minimum crack propagation out of the fracture plane. The crack propagation is carefully observed both in 2D and 3D as the GaN substrates underwent various laser pulse energies, and laser shot distances.

A 2-inch GaN substrate with a thickness of 410 μm was cut into several 5 mm x 5 mm square samples. A top hat-shaped, 532 nm green laser with a peak power density of 2.5 x 10^{11} W/cm^2, a beam diameter of 1 μm, and pulse duration of 500 ps was used for slicing, and a spatial light modulator based on liquid crystal on silicon (LCOS-SLM, Hamamatsu Photonics) was equipped for compensating the spherical aberration due to the high refractive index of GaN. The laser beam was focused inside a GaN substrate with a 50 times magnification objective lens via a 6-point branched laser beam in the y-direction. All 6-point branched laser beams were equal in terms of power density and diameter, all of which being 1/6 of the initial beam value. By using the LCOS-SLM setup and by the aid of a PC using the digital video interface (DVI), which is a standard interface for PC displays, we were able to make an arbitrary shape of the laser beam. Unlike conventional intensity modulation techniques using masks to block out the light to form a desired optical pattern, the LCOS-SLM redistributes the light to generate light patterns efficiently by using phase type holograms. The pitch of laser shots in the x-direction was controlled by the speed of electric stage on which samples were mounted. In this manner, the spacing of laser shots were set to 5 μm, 10 μm, and 15 μm both in the x and y directions. The pulse energies were set to 1 μJ, 2.5 μJ, 5 μJ, and 10 μJ. All laser shots were irradiated at 205 μm from the surface, half the thickness of the GaN substrate. A schematic illustration of the slicing process is shown in Fig. 1a. Laser shot centers were visualized using a multiphoton confocal microscope (Nikon A1MP$^+$), and 3D reconstruction was made using an imaging software NIS Elements, Nikon Instruments Inc. All samples were cut in the x-direction and the cross-sections were observed by a scanning electron microscope (SEM; Hitachi SU-70) operating at 5 kV.

3. Results and discussion

Fig. 1b shows the digital photographs of GaN substrates subjected to the laser irradiation at various pulse energies and shot pitches. At the shot distance of 5 μm and pulse energy of 1 μJ the sample remained transparent, but as the pulse energy was increased to 2.5 μJ 5 μJ, and 10 μJ samples turned opaque. The change in the transparency proves the strong interaction between the laser and GaN substrate; the interaction is extremely low at 1 μJ but increases suddenly at higher energies. The transparency loss also exhibits the metallization of the GaN substrate at the laser affected area, where Ga-N bonds are broken by laser irradiation and nitrogen atoms leave the lattice and metallic Ga deposits surround the laser shots. When the laser shot distance is increased to 10 μm, the matter-light interaction gets less significant. In this case GaN substrates are still transparent until the pulse energy of 5 μJ, but become semi-transparent at 10 μJ but the level of metallization is less appreciable. When the shot pitch increased to 15 μm, the interaction between adjacent laser shots was almost negligible and no metallization was observed even at energies as high as 10 μJ.

Fig. 2 shows a set of multiphoton confocal microscope images observed at 205 μm with respect to the surface of the GaN substrate. At the shot distance of 5 μm, when the pulse energy is low radial cracks (shown in yellow lines) are formed in the irradiation plane. When the pulse energy is increased to 5 μJ lateral cracks (shown in purple lines) are also formed in addition to the radial cracks. Cracks could not be observed at the 10 μJ sample due to the severe melt out of metallic Ga around the laser shots. The same phenomenon was observed for the samples with spacings of 10 μm and 15 μm, where radial cracks formed at lower energies, while radial and lateral cracks formed at higher energies. The morphology of the cracks depending on the pulse energy and shot to shot distance which is well consistent with the reported observations for other materials like MgO [37], LiF [38], and sapphire [39] is observed in GaN for the first time. Previous studies showed that the picosecond regime generates cracks mostly along three crystallographic axes for different materials like sapphire, which is compatible with the orientations of the crystalline directions [40], while, in the femtosecond regime cracks propagate only one direction [39]. In this study a sub-nanometer regime is applied. Further studies are necessary for investigating the relationships between crack morphology, pulse energy, and shot distance in femtosecond regime. The difference between the picosecond and femtosecond regimes originates from the difference in the plasma morphology, i.e., the cross section of femtosecond pulses is elliptical while that of the picosecond irradiation is a symmetric circular pattern [40].

Fig. 3 shows a set of reconstructed 3D images of the multiphoton confocal microscope. An inverse contrast is used with respect to that of Fig. 2 for better visibility of the laser affected zone. Also, the depth of scanning is different for all samples and is determined in a manner that laser affected zone is better observable. At the shot distance of 5 μm, the average depth of damage field in pulse energies of 1 μJ, 2.5 μJ, and 5 μJ are 7.1 μm, 7.6 μm, and 14.3 μm, respectively. These values are well consistent with the crack propagation depth observed by SEM in Fig. 4. At the pulse energy of 10 μJ the transparency of the sample was extremely low due to metallic Ga melt out, and therefore a 3D image could not be acquired. At the shot distance of 10 μm, the average depth of laser affected zone at 1 μJ was almost in the same range as those at the shot distances of 5 μm, however, as the pulse energy increased to 2.5 μJ and more the depth of laser affected zone increased significantly. According to these results, it can be inferred that the damage depth is low when radial cracks are dominant, while the damage depth increases significantly once the lateral cracks start to dominate. Similar results are observed in the set of data for the shot distances of 15 μm.

Fig. 4 shows the cross-section SEM micrographs of samples. At the shot distance of 5 μm with energy of 1 μJ, the crack propagation within the laser irradiated plane is well controlled and adjacent shots are on a straight line with a negligible fluctuation. At 2.5 μJ also the crack propagation is well-controlled, however, at 5 μJ and 10 μJ the crack has started to fluctuate with respect to the sample surface. This trend is same for samples with shot distances of 10 μm and 15 μm. These results are consistent with results of 2D and 3D confocal microscope images and it can be concluded that radial cracks propagate parallel to the (0001) surface, while lateral cracks propagate perpendicular to the (0001) surface. There are few models studying the crack formation and crack propagation of the freestanding GaN substrates. One of those models for the formation of crack seeds is the interaction of dislocations on different glide planes and the pile-up of dislocations at Lomer-Cottrell barriers [41]. If a crack seed is formed due to the interaction of laser and GaN, subsequent crack propagation can take place and lead to a macroscopic crack. The light-matter interaction can be divided into three stages [42]. In the elastic stage, the deformation is completely reversible. It is supposed that this stage corresponds to the very low laser pulse energies, where we do not observe any crack initiation. The second stage is the initiation of the elastic-plastic stage which is associated with the onset of plasticity and the generation of dislocations. In the elastic-plastic stage, the material is deformed by the generation and propagation of dislocations, but the deformation is partly elastic. The third stage is the formation and propagation of cracks and the deformation is mostly plastic. It seems that lower pulse energies result in the first stage, while higher energies lead to the second or third stages. In GaN, dislocations act mainly as centers of non-radiative recombination. Hence, they appear dark in cathodoluminescence (CL) images. However, CL imaging can only be acquired from the substrate surface, while the initiation of the cracks and dislocations in our samples are inside the substrate. Therefore, we believe that further studies are necessary for the investigation of the dislocation behavior by focusing the laser on the surface of the GaN substrate instead of the inside. Also, the interaction of laser with preexisting as-grown dislocations, the orientation of the incident light, and dislocation pile-up around cracks during irradiation must be carefully studied for explaining the mechanism of the crack formation and propagation, and to explain why two types of radial and lateral cracks form at certain conditions. To this end, our observations revealed that the pulse energy and the spacing of the adjacent shots play an important role on the quality of the slicing plane.

Fig. 5 shows the magnified cross-section SEM micrographs of representative samples for better visibility of crack propagation. It is evident that a significant delamination occurs at higher energies and cracks fluctuate strongly with respect to the irradiation plane, while at lower energies the crack propagates parallel to the irradiation plane. In order to obtain a smooth slicing surface, it is very important to control the cracks parallel to the irradiation plane because any zigzag propagation of cracks will lead to the rough surface, requiring further polishing process, and wasting a larger portion of the GaN substrate.

Fig. 6 shows a digital photograph of a 5 x 5 mm GaN substrate after laser irradiation cleaved at its half thickness. After the laser irradiation finished, GaN substrates were stuck to a glass slide by a double-stick tape. Then, two pieces of glass slides were pulled away from each other mechanically, leaving half of the GaN substrates on each side. Finally, tapes were removed from the GaN surface. As shown, a deposit of gallium metal can be observed on the cleaved surfaces as a consequence of gallium-nitrogen bond breakage. Gallium deposits can be easily removed by HCl acid washing.

4. Conclusion

In this study, a sub-nanometer 532 nm green laser equipped with LCOS was used for investigating the effect of laser pulse energy and adjacent shot spacings on the quality of the GaN wafer slicing in a desired thickness. Results showed that depending on the pulse energy and shot spacing, two types of radial and lateral cracks were induced in the irradiated plane. Radial cracks propagated parallel to the (0001) surface of GaN substrate, while lateral cracks propagated perpendicular to the (0001) surface. Therefore, it can be concluded that there exists a window of pulse energy and shot spacing in which lateral cracks could be suppressed. A comprehensive look at the results of 2D, 3D confocal microscope images, and SEM micrographs suggested that pulse energy of 1 μJ and a shot spacing of 5 μm can be a reasonable solution for slicing the GaN substrate with controlled crack propagation in the target plane with deviations in the order of submicrons.

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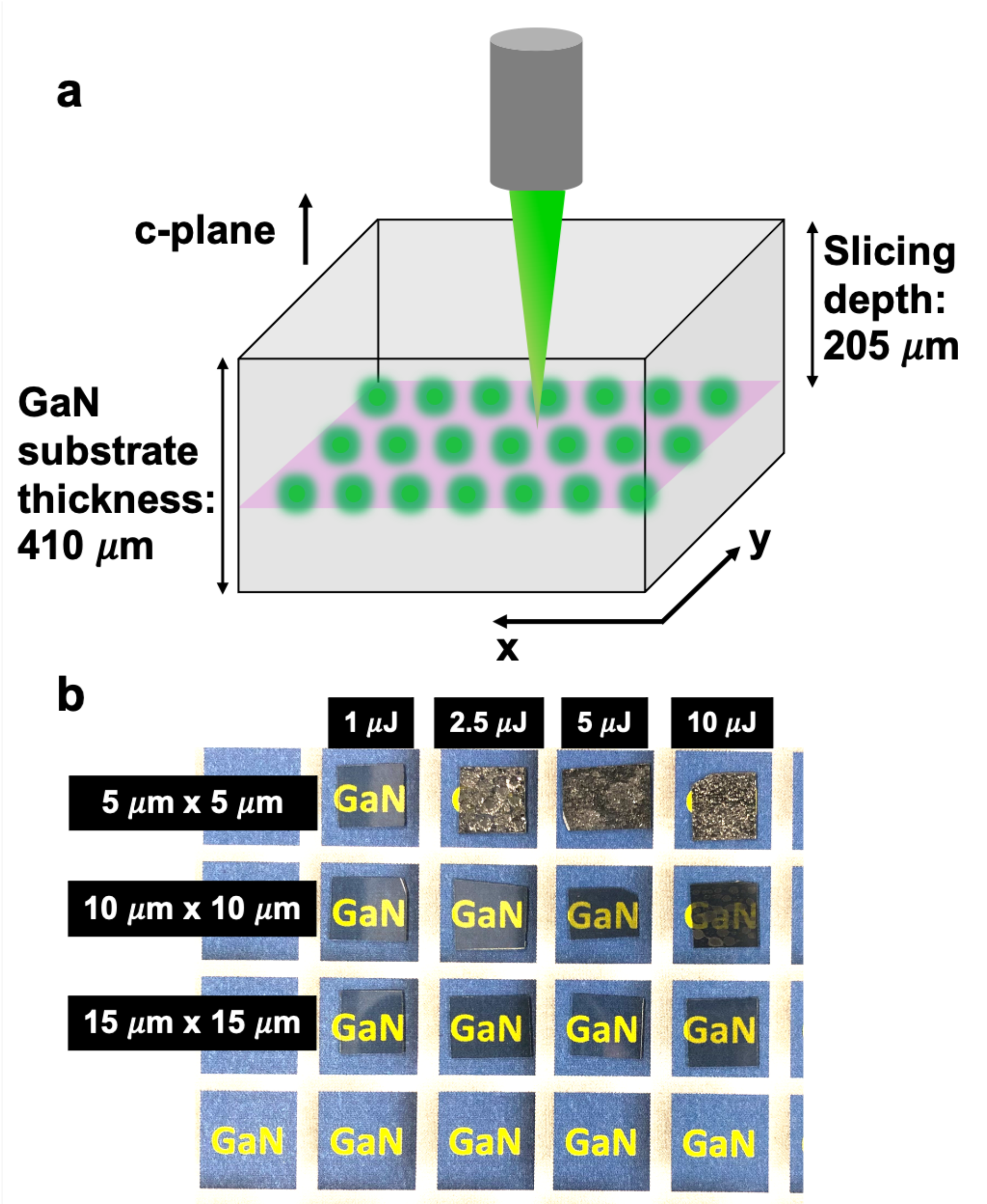

Fig. 1(a). A schematic illustration of the GaN substrate slicing process, (b) digital photographs of GaN substrates after laser irradiation at laser pulse energies of 1 µJ, 2.5 µJ, 5 µJ, 10 µJ, and laser shot spacings of 5 µm, 10 µm, and 15 µm.

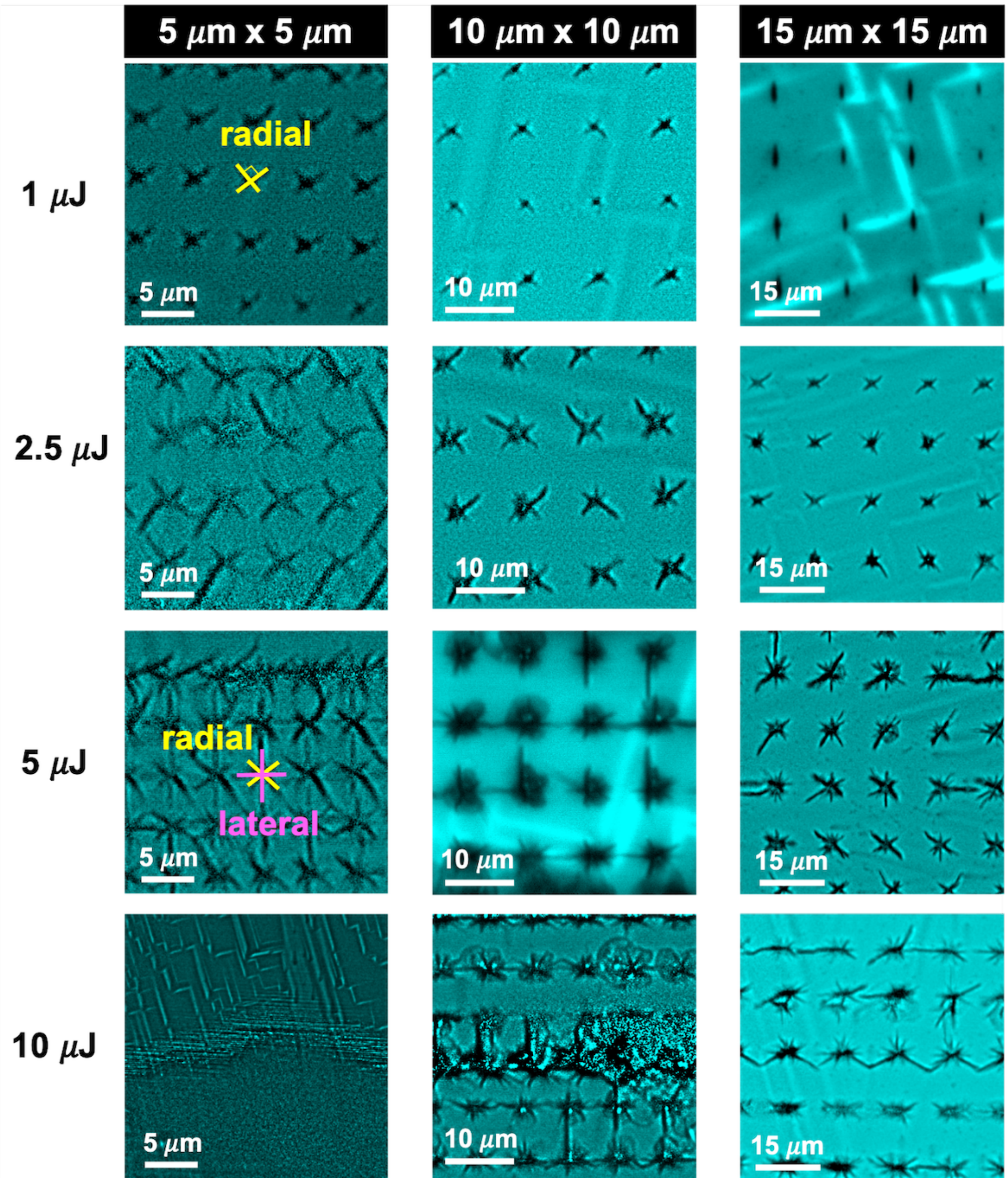

Fig. 2. Crack morphology observed by a multiphoton confocal microscope at various pulse energies and laser shot spacings.

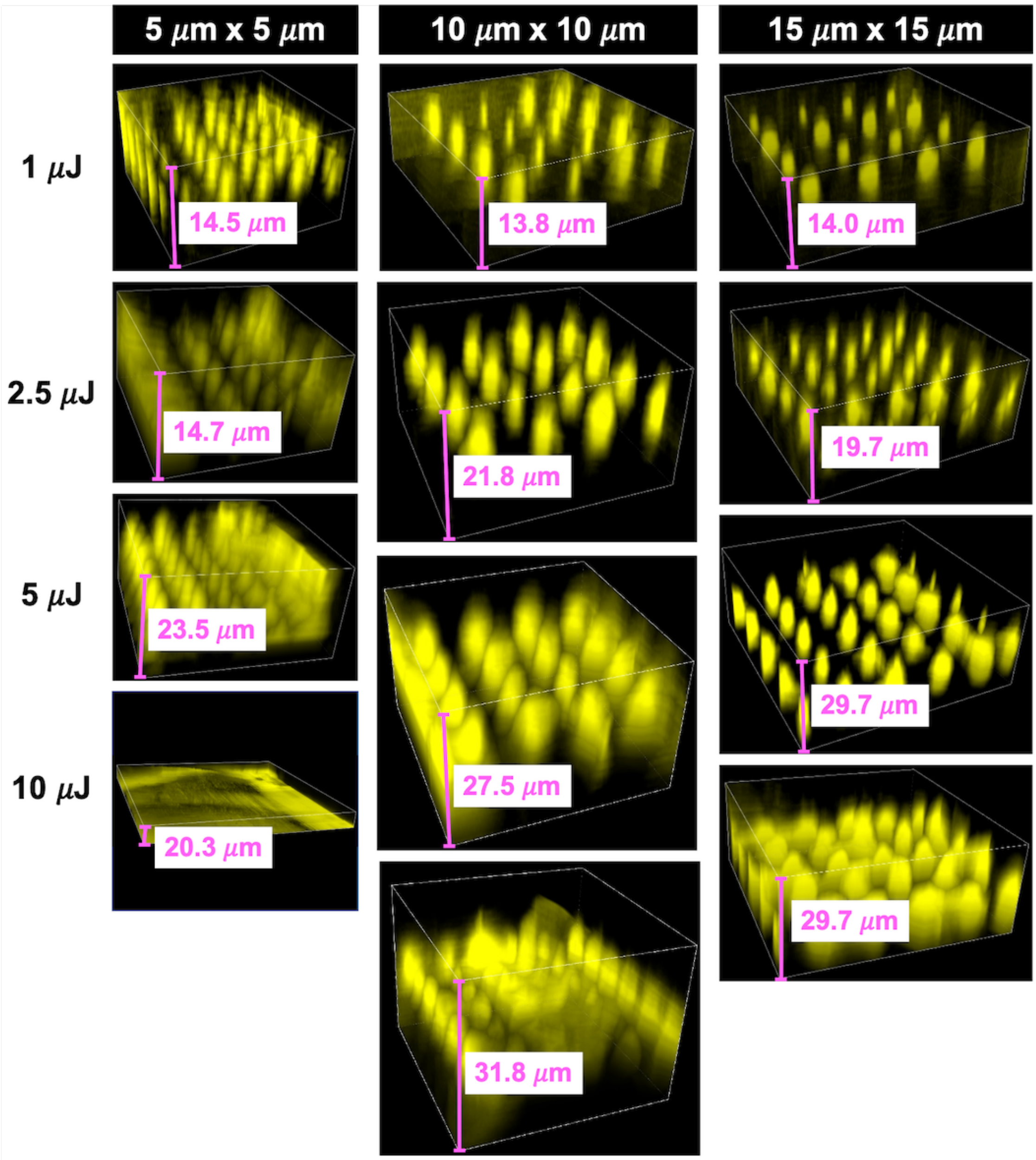

Fig. 3. 3D imaging of crack propagation by a multiphoton confocal microscope at various pulse energies and laser shot spacings.

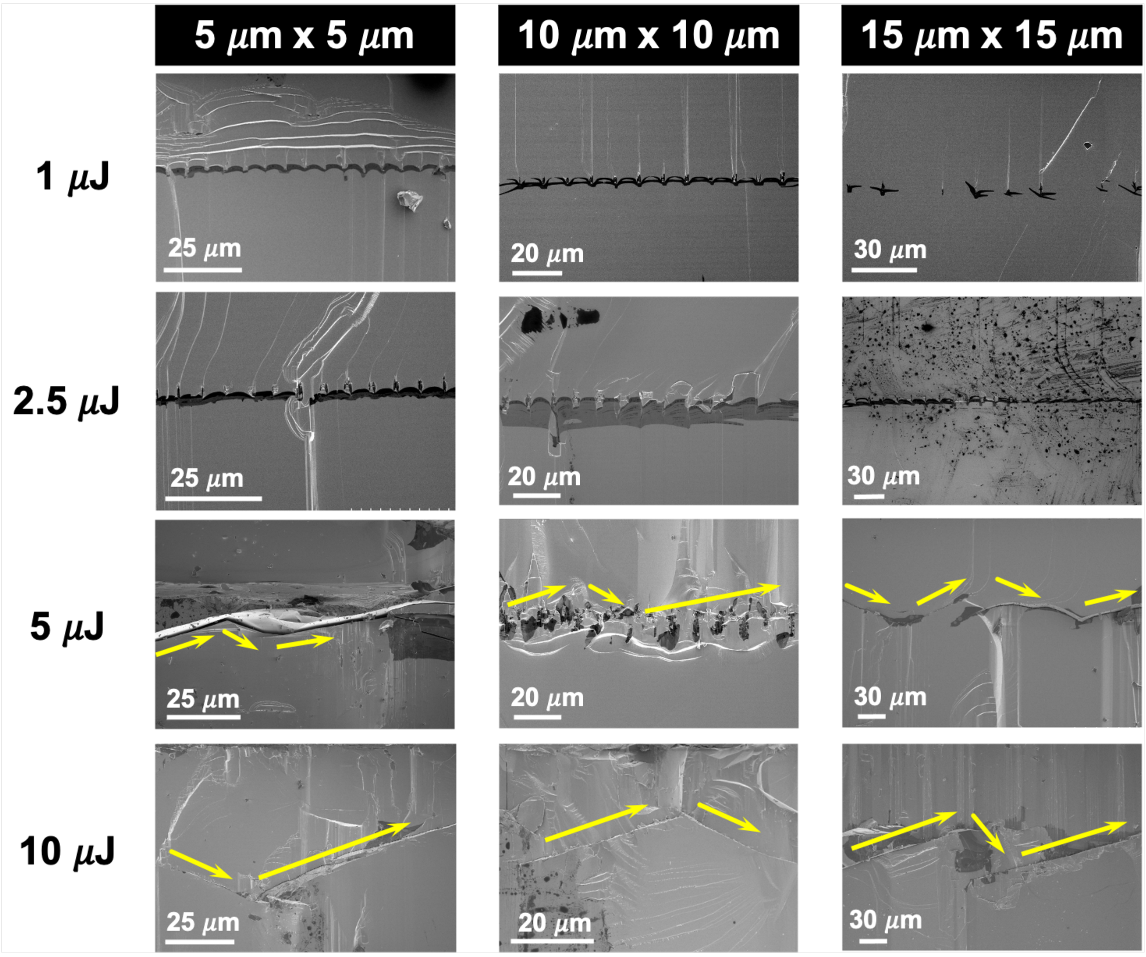

Fig. 4. Cross-section SEM micrographs of GaN substrates after laser irradiation at various pulse energies and laser shot spacings.

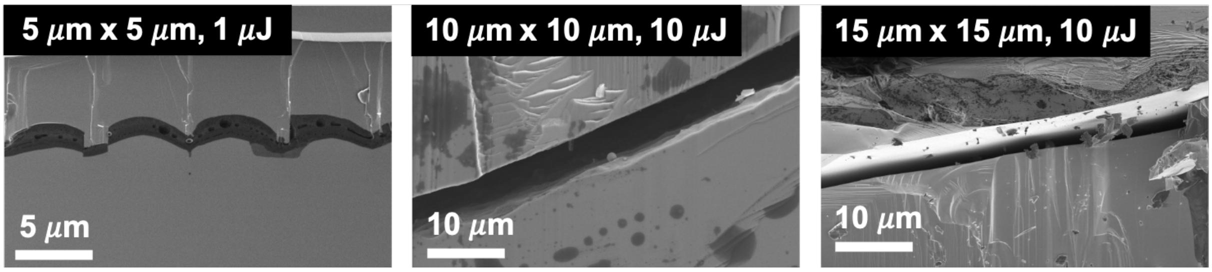

Fig. 5. Representative magnified cross-section SEM micrographs of GaN substrates after laser irradiation.

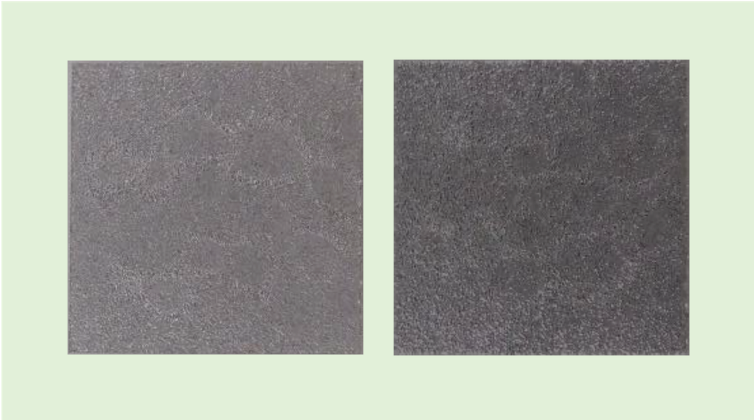

Fig. 6. Digital photograph of a 5 x 5 mm GaN substrate after laser irradiation cleaved at its half thickness.