High -Rate Laser Ablation For Through-Wafer Via Holes in SiC Substrates and GaN/AlN/SiC Templates

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Abstract —**CO_2 laser ablation rates for bulk 4H-SiC substrates and GaN/AlN/SiC templates in the range 229-870 μm.min $^{-1}$ were obtained for pulse energies of 7.5-30 mJ over diameters of 50-500 μm with a Q-switched pulse width of ~30 nsec and a pulse frequency of 8 Hz. The laser drilling produces much higher etch rates than conventional dry plasma etching (0.2 – 1.3 μm/min) making this an attractive maskless option for creating through-wafer via holes in SiC or GaN/AlN/SiC templates for power metal-semiconductor field effect transistor applications. The via entry can be tapered to facilitate subsequent metallization by control of the laser power and the total residual surface contamination can be minimized in a similar fashion and with a high gas throughput to avoid redeposition. The sidewall roughness is also comparable or better than conventional via holes created by plasma etching.**

Laser drilling is often used to machine hard materials such as super alloys. A simple model suggests that above a threshold laser power density, the surface of the material is melted and subsequently ejected by ablation [1]. There is interest in creating deep etched features in materials such as SiC, GaN and AlN for electronic devices or micro electromechanical systems applications. For example, SiC metal-semiconductor field effect transistors (MESFETs) and AlGaN/GaN high electron mobility transistors (HEMTs) grown on either SiC or AlN substrates are very promising for high power, high temperature applications in hybrid electric vehicles, power flow control and remote sensing [2-5]. Small-scale monolithic mm-wave integrated circuits for these applications benefit from having through-wafer via connections to provide a common ground and a low inductance path from the source of the FET to the ground plane in the back of the wafer [6]. To this point, such vias in SiC have been formed by conventional dry etching techniques, such as Reactive Ion Etching (RIE), Electron Cyclotron Resonance (ECR) or Inductively Coupled Plasma (ICP) etching [7-18]. Typical etch rates for 4H and 6H SiC substrates in F_2 or Cl_2-based plasmas using these techniques range between 0.2 – 1.3 μm/min(the low end is obtained with RIE and the high end with ICP), meaning that even for a thinned-down substrates of 50 μm, the etch time is generally long and as much as 4 – 5 hours under ion energy conditions where mask erosion is not prohibitive. There have been no reports to date of achieving vias in either GaN or AlN substrates. One disadvantage with dry etching for creating via holes in these materials is the need for a very robust, typically metal, mask material such as Ni, Al or Cr. The deposition, patterning and subsequent removal of such masks adds considerable complexity to the via fabrication process. In addition, the roughening of the sidewalls of such masks during the long etch time usually leads to vertical striations on the sidewalls of the etched features.[19]

The development of maskless methods for creating via holes in SiC ,GaN and AlN and in particular for standard thickness substrates would give added flexibility for creating custom patterns in the substrates through computer control of the laser drilling location and would also eliminate the need for wafer thinning prior to via formation. In this letter we report on high ablation rates

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achieved by laser drilling of both 4H-SiC substrates and thick GaN/AlN/SiC templates. The laser drilling is shown to be capable of very high etch rates and precise control of the via size and sidewall slope. The use of optical and mass spectrometric methods to control the process reduces problems with re-deposition of ablated material, making this an attractive technique for creating maskless ,through-wafer via holes in this material.

Two different types of samples were used for these experiments. The SiC substrates employed were 4H-polytype, N-doped, ~$10^{17}cm^{-3}$. The thickness was ~400 μm, and laser drilling was employed in both directions, *i.e.* from front-to-back and vice versa, but no significant differences in the ablation rate or anisotropy of the via holes were observed. We also used a multilayer templates consisting of 3 μm of GaN and 30 μm of AlN grown by hydride vapor phase epitaxy on top of a 4H-SiC substrate. Via holes with nominal diameters of 50 – 500 μm were obtained by laser drilling with a CO_2 laser (λ = 1.06 μm). The pulse frequency was 8 Hz, the ϕ-switched pulse width was about 30 ns with a delivered pulse energy of ~7.5-60 mJ/pulse. The ablation rates were measured by cleaving the samples and measuring the etch depth by scanning electron microscopy (SEM).The anisotropy and surface morphology of the resulting holes were also examined by SEM.

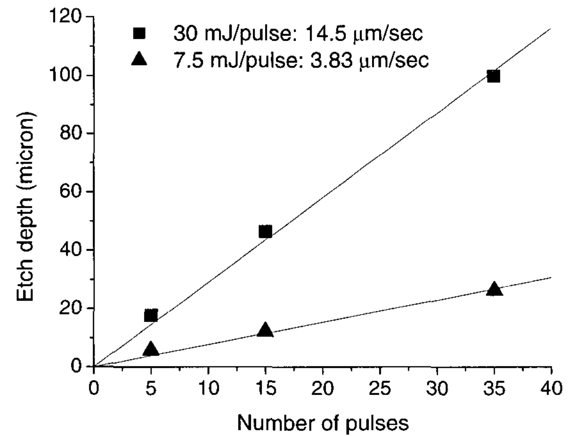

Fig. 1. Ablation depth of SiC with CO_2 (λ = 1.06 μm) laser drilling at two power levels. The slope of these curves is the effective SiC etch rate.

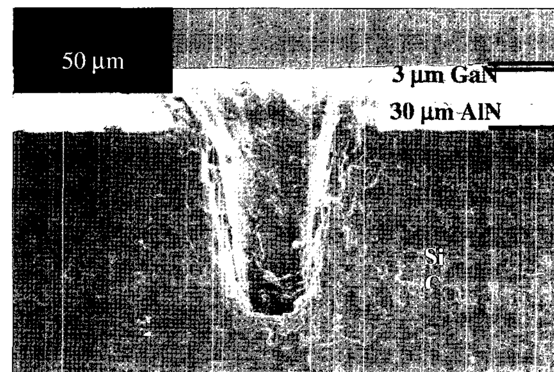

Fig. 2. SEM cross section of hole drilled to a shallow depth in GaN/AlN/SiC structure in order to calibrate ablation rate.

Fig. 1 shows the laser drill depth in SiC as a function of the number of laser pulses at two different pulse energy powers. Note that the laser ablation rates (229-870 μm/min)are significantly faster than for the highest plasma etching rates achieved with ICP etching in F_2-based chemistries. Hence while laser drilling is inherently a serial process when performed in a maskless configuration, the high ablation rates mean that throughput will be comparable to a plasma etch via process in which all the vias are formed simultaneously, at least for the small diameter substrates currently available. A further advantage of the laser drilling technique is that the via hole pattern and the size of the vias can be readily controlled by computer-controlled x-y positioning of the SiC substrate, allowing much more flexibility and reducing costs relative to the need for producing a separate mask in plasma etch processes.

To demonstrate the effectiveness of the laser drilling through multi-layered structures, Fig. 2 shows an SEM micrograph of a hole drilled into the GaN (3μm)/AlN (30 μm) /SiC substrate structure. Note the smooth transition between the different materials. The morphology of the sidewall was somewhat better for the lower power density drilling. This result demonstrates that laser drilling is also effective for creating via holes in other substrates of interest, such as GaN and AlN, and may be of interest for MMIC applications in AlGaN/GaN high electron mobility transistors grown on these substrates. Note that by ramping down the laser power density as the drilling proceeds, we were able to taper the edges of the hole. This is highly desirable for subsequent metallization to complete the through wafer via connection. There is also an absence of redeposited material on the surface ,which shows the effectiveness of employing a high gas flow rate(25 $l.min^{-1}$) of filtered N_2 across the surface during the laser drilling to flush out the plume of ablated material. Without this cross-purge, the holes are surrounded by the redeposited material ablated from the hole.

Fig. 3 (left) shows scanning electron microscope (SEM) micrographs of a series of through-wafer vias with different diameters in SiC. The ablated surfaces are relatively clean . As discussed above,recent advances in control of the laser drill process have reduced problems with surface contamination by ablated material. This ablated material would fall back on the surface of the laser focus area and this contamination was clearly undesirable. One common practice for controlling ablation debris involves the use of an inert gas flow over the laser ablation region. This is intended to prevent oxidizing reactions, cooling the plume and substrate and flushing the ablated material away. However, as the laser focus size is reduced and instantaneous laser power increases, this technique becomes less effective. For vias below ~50 um in diameter, we found it necessary to employ an improved technique that combines optical and mass spectroscopic methods during laser drilling to monitor and control the ablation plume and ionized debris has been applied here. This significantly reduces the total surface contamination. These methods are effective on a microscopic scale with the use of high-energy laser pulses of very short duration. Figure 3(right) shows an SEM cross-section of a complete through-wafer via. The entry hole is wider than the exit hole facilitating subsequent metallization to complete the electrical connection through the via.

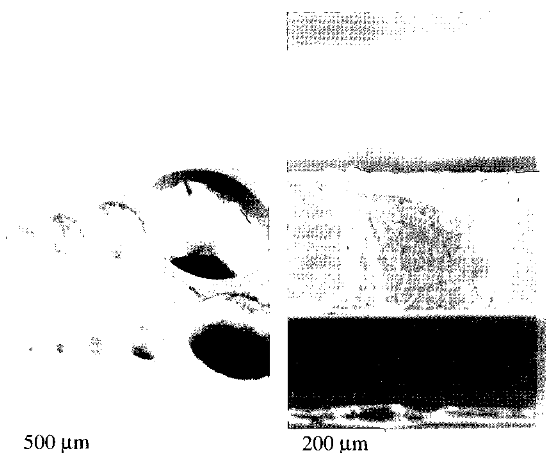

Fig. 3. SEM micrographs of laser-drilled via holes in SiC substrates(left).A cross-section of one of the holes is shown at right..

The sidewall roughness of the laser drilled holes was comparable or better than that achieved with plasma etching. For comparison, Fig. 4 shows SEM micrographs of features etched in 4H-SiC substrates using ICP SF_6/Ar etching using a thick electroplated Ni mask(left) [12],along with an SEM of the sidewall of a laser drilled feature(left).The absence in the laser drilled feature of vertical striations that are transferred from mask sidewall roughness during conventional plasma etching is clearly an advantage of the former method. Since the laser drilling works by ablation of the SiC, there is also less of a problem with micromasking leading to so-called "grass" on the SiC surface as there is with plasma etching.

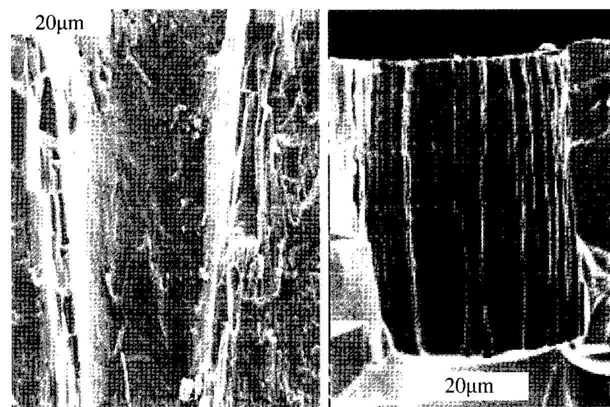

Fig. 4. SEM cross sectional micrographs of laser-drilled via hole in SiC (left) and for comparison of the sidewall roughness, a deep feature created in SiC by plasma etching (right).

In a real via hole process, the wafer already has front-side metallization and therefore the etching or drilling process must have reasonable selectivity for the SiC over the metal contact. In the work described here we have performed laser drilling of bare SiC substrates without concern for selectivity to the metal contacts that would be in place in a real process. However, the high reflectivity of mask metals to laser light provides a built-in mechanism for achieving a low ablation rate of these materials.

In conclusion, the high laser ablation rates achievable with controllable laser drilling appears to be applicable to creating via holes in SiC substrates or GaN/AlN/SiC templates. This is a maskless method with similar throughput to plasma etching of thinned-down substrates. The use of cross-purge gas flow and control of the laser power density minimizes redeposition of ablation debris and allow creation of clean via holes with highly anisotropic sidewalls and the ability to taper the entry hole.

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REFERENCES

[1] J.C.J.Verhoeven, J.K.M.Jansen, R.M.M.Mattheij and W.R.Smith, Mathematical and Computer Modelling 37 419(2003).

[2] J. B. Casady, E. D. Luckowski, M. Bozack, D. Sheridan, R. W. Johnson, J. R. Williams, J. Electrochem. Soc. 143 1750 (1996).

[3] J. B. Casady, A. K. Agarwal, S. Seshadri, R. R. Siergiej, L. B. Rowland, M. F. MacMillan, D. C. Sheridan, P. A. Sanger, C. D.Brandt, Solid-State Electronics 42 2165 (1998).

[4] R. Singh, J. A. Cooper, M. R. Melloch, J. W. Palmour, T. P. Chow, IEEE Trans. on Electron Dev. 49 665 (2002).

[5] A. P. Zhang, L. B. Rowland, E. B. Kaminsky, J. W. Kretchmer, R. A. Beaupre, J. L. Garrett, J. B. Tucker, B. J. Edward, J. Foppes, A. F.Allen, Solid-State Electron. 47 821 (2003).

[6] S. Thomas III and J. J. Brown, in Handbook of Advanced Plasma Processing Techniques, ed. R. J. Shul and S. J. Pearton (Springer, Berlin 2000).

[7] P. H. Yih, A. J. Steckl, J. Electrochem. Soc. 142 2853 (1995).

[8] P. Leerungnawarat, D. C. Hays, H. Cho, S. J. Pearton, R. M. Strong, C.-M. Zetterling, and M. Östling, J. Vac. Sci. Technol. B 17 2050 (1999).

[9] S. Tanaka, K. Rajanna, T. Abe, and M. Esashi, J. Vac. Sci. Technol. B 19 2173 (2001).

[10] B. Li, L. Cao and J. H. Zhao, Appl. Phys. Lett. 73 653 (1998).

[11] J. R. Flemish, K. Xie and J. H. Zhao, Appl. Phys. Lett. 64 2315 (1994).

[12] F. A. Khan and I. Adesida, Appl. Phys. Lett. 75 2268 (1999).

[13] H. Cho, P. Leerungnawarat, D. C. Hays, and S. J. Pearton, S. N. G. Chu, R. M. Strong, C.-M. Zetterling and M. Östling and F. Ren, Appl. Phys. Lett. 76 739 (2000).

[14] P. Chabert, N. Proust, J. Perrin and R. W. Boswell, Appl. Phys. Lett. 76 2310 (2000).

[15] J. J. Wang, E. S. Lambers, S. J. Pearton, M. Ostling, C.-M. Zetterling, J. M. Grow, F. Ren, and R. J. Shul, J. Vac. Sci. Technol. A 16 2204 (1998).

[16] G. F. McLane and J. R. Flemish, Appl. Phys. Lett. 68 3755 (1996).

[17] F. A. Khan, L. Zhou, V. Kumar, J. Electrochem. Soc. 149 G420 (2002).

[18] I. P. Leerungnawarat, K. P. Lee, S. J. Pearton, F. Ren, S. N. G.Chu, J. Electron. Mater. 30 202 (2001).

[19] see for example, R.J.Shul (ed).Handbook of Advanced Plasma Processing Techniques(Springer, Berlin, 2000).

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