Silicon carbide (SiC) belongs to a new generation of semiconductors called wide band-gap semiconductors. Due to its excellent thermal conductivity, large breakdown electric field and large band gap, SiC shows considerable promise in high power, high frequency, and high temperature applications. Due to its excellent thermal conductivity, large breakdown electric field and large band gap, SiC shows considerable promise in high power, high frequency, and high temperature electronic devices.1 In addition, the large Si–C bonding energy makes silicon carbide components resistant to chemical attack and radiation, and thus attractive for applications in harsh environments. Unfortunately, the large Si–C bonding energy can also be viewed as a problem since it makes SiC very difficult to etch. In particular, it has been shown that SiC is inert in conventional acid or base solutions at normal temperature and that plasma etching must be used.

While etching a depth of only a few thousand Å for classical SiC electronic device fabrication is a solved problem, new technologies including fabrication of microelectromechanical systems (MEMS) or via holes for high frequency electronic devices are now emerging. These applications require deep etching (up to 350 µm) and consequently high etch rate processes. Previous experiments have demonstrated that etch rates obtained in capacitively coupled reactors are much too low,2,3 due to the low positive ion density \( n_+ = 10^{10} \text{cm}^{-3} \). A new generation of high plasma density reactors \( n_+ = 10^{12} \text{cm}^{-3} \), including Magnetron (13.56 MHz), Inductively Coupled Plasmas (13.56 MHz), Helicons (13.56 MHz), and Electron Cyclotron Resonance (2.45 GHz) is now used to etch SiC.4–9 A maximum etch rate of 0.97 µm/min was achieved in an Inductively Coupled Reactor using SF6-based gas mixtures.9

In this letter, we investigate 4H–SiC etching using a helicon reactor operating with SF6/O2 gas mixture. The etch rates have been recorded as a function of pressure, power injected in the source, substrate bias voltage, and distance between the source and the substrate holder. Uniformity on 2 in. SiC substrates and roughness of etched surfaces have also been investigated.

Bulk 4H–SiC substrates from Cree Research were employed in all experiments presented in this letter. We compared the effectiveness of different mask materials, including Ni, Al, ITO, Cr, SnO2, SiO2, and photoresists, and we decided to use nickel, which had the greatest etch resistance.10,11 Metal lift-off technique was used to pattern the sample with the nickel mask. The samples were then etched in the helicon reactor. Etch depths were measured using a TENCOR profilometer after the nickel mask had been removed using a nickel-etch solution. We always used a SF6/O2 reactive gas mixture containing 25% of O2. The addition of oxygen did not increase the etch rate but prevented undesirable sulfur-based deposition on the chamber walls (by formation of volatile products such as SOxFy) which was suitable to maintain the reactor as clean as possible.

We used a helicon reactor fairly similar to the Australian National University helicon reactor described in detail in Ref. 12. Briefly, it consists of a 15-cm-diam, 30-cm-long glass tube (the source chamber) surrounded by a Boswell-type helicon antenna13 and two magnetic field coils, that sits atop a 20-cm-diam, 40-cm-long stainless diffusion chamber surrounded by two more field coils. The currents in the coils were adjusted to produce a cusped magnetic field in the source and a nearly uniform field in the diffusion chamber. This configuration was found to maximize the plasma density in the diffusion chamber. Usually, the substrate holder is mounted at the bottom of the diffusion chamber, that is 30 or 40 cm away from the helicon source. Since it has been shown that for pressures above 1 mTorr the positive ion flux decreases when the distance from the source increases,12 we expected that this distance would be a key parameter for optimizing the etch rate. Therefore, a movable substrate holder capable of probing all the distances from the source...
antenna was constructed. Both the source antenna and the substrate holder are polarized by 13.56 MHz generators.

Figure 1 shows the etch rate as a function of the distance between the source and the substrate holder when the pressure is 6 mTorr (30 sccm SF\(_6\)/7.5 sccm O\(_2\)). The source power is 500 W, and the substrate bias voltage is \(-160\) V. The lower branch of the helicon antenna is placed 2.5 cm above the end of the source tube (position 0 cm). It appears, in agreement with predictions, that the etch rate decreases when the distance increases. One can see that the etch rate is 0.5 \(\mu\)m/min when the distance is 0 cm and about half at 10 cm away from the helicon source. This is due to the fact that in the diffusion regime \((P = 6\) mTorr) the positive ion density decreases when the distance from the source increases. The situation deteriorates at higher pressure since the diffusion length varies with \(1/P\). It is worth noting that in most of ICP, ECR, or helicon reactors, the distance between the source and the substrate holder is equal to or greater than 10 cm. This simple observation partially explains why etch rates reported in this letter exceed those obtained in conventional reactors. In addition, satisfactory etching uniformity is still obtained when the substrate holder is placed at the bottom of the source tube (at 0 cm). At this position, the etch rate dispersion on 2 in. substrates is less than 6% and preliminary tests showed that the dispersion was less than 10% on 3 in. Si substrates (3 in. SiC substrates are not available by now).

As a summary for this part, our results show that a high rate and uniform etching regime is obtained by minimizing the distance between the source and the substrate holder. In the following, the substrate holder is placed at the bottom of the source tube, i.e., distance fixed at 0 cm.

Figure 2(a) shows the etch rate as a function of the total pressure when the source power is 500 W and the substrate bias voltage is \(-160\) V. When the pressure increases the fluorine atom concentration increases. Since F atoms are the main chemical agents for SiC etching (formation of major products CF\(_x\) and SiF\(_x\)), increasing the F atom density tends to enhance the etch rate. However, in electronegative gas increasing pressure usually reduces the positive ion flux. This is mainly due to the fact that the negative ion density increases with pressure leading to a dramatic decay of the Bohm velocity.\(^{14}\) This latter effect tends to reduce the etch rate when the pressure increases. As a summary, increasing pressure increases the F atom density but reduces the positive ion flux. Thus we found an optimum pressure, between 4 and 6 mTorr, for which the etch rate is maximum.

Figure 2(b) shows the etch rate as a function of substrate bias voltage for two different source powers. The ion bombardment energy increases with the substrate bias voltage, which increases the physical ion sputtering and accelerates chemical reaction at the surface: i.e., the evaporation of species resulting from surface chemical reaction such as CF\(_x\) and SiF\(_x\) (where \(x\) is between 1 and 4) is enhanced by the ion bombardment. As a consequence, for both curves the etch rate increases when the absolute value of the substrate bias increases. Unfortunately, when the ion bombardment energy is too high, the physical sputtering of the nickel mask becomes important, and results in the deposition of Ni from the mask onto the SiC surface, leading to micromasking effects and then to an undesirable rough etched surface. In our case, we found that this effect becomes important when the substrate bias voltage exceeds \(-300\) V.

We also observe an effect of the power injected on the helicon antenna on the SiC etch rates. The helicon reactor can operate in three regimes called capacitive \((E)\), inductive \((H)\), and helicon wave \((W)\). As the power injected on the antenna is increased, transitions from capacitive to inductive to helicon discharges (transitions \(E\rightarrow H\rightarrow W\)) occur. Ionization products CF\(_4\) and SiF\(_4\) dominate the etching process.
ation and dissociation rates increase when describing the $E \rightarrow H \rightarrow W$ transitions and are maximum in the helicon regime. When operating at 500 W, we are in the inductive mode and thus our results are close to those obtained in an ICP reactor by Khan and Adesida, although we obtain slightly higher etch rates due to the fact that in our configuration the distance between the substrate holder and the helicon antenna is minimum. Etch rates obtained are fairly high since positive ion and reactive neutral densities are quite high. At 1200 W, we are in the helicon regime and the reactive gas is more efficiently ionized and dissociated. This leads to greater positive ion and reactive neutral (F atom) fluxes to the substrate, which further increase the etch rate. Etch rates of 1.35 $\mu$m/min have been achieved in the helicon regime, which is the highest yet reported.

Figure 3(a) is a scanning electron micrograph of a SiC sample patterned with nickel and etched to a depth of 12 $\mu$m. The pressure was 6 mTorr, the substrate bias voltage was $-120$ V, and the source power was 1200 W. Under these conditions the etch rate is 0.8 $\mu$m/min and the selectivity SiC/Ni is about 50. Therefore, the nickel mask only needs to be 2400 Å thick (actually 3000 Å of nickel was deposited) and the substrate was etched in 15 min. No micromasking effect has been observed. Atomic force microscopy indicates that the surface roughness of SiC etched under these conditions is about 3.5 Å rms, which is similar to the roughness of unetched surfaces. Finally, as observed by other groups, $^{8,9}$ etch profiles are essentially anisotropic and a slight trenching (overetch) effect appears at the base of the sidewalls.

Figure 3(b) is a scanning electron micrograph of a via-hole structure of 600 $\mu$m in diameter. The 330 $\mu$m thick SiC substrate was fully etched in about 6 h. The pressure was 6 mTorr, the substrate bias voltage was $-160$ V, and the power source was 1200 W. We used a nickel sheet (50 $\mu$m thick) stuck on the SiC sample; i.e., a shadow mask. The selectivity SiC/Ni was about 40 under these conditions. This shadow mask process is obviously not suitable for electronic device fabrication, but it demonstrates that we are able to etch via holes in SiC. According to the selectivity, 300 $\mu$m via-hole etching requires finding an acceptable process to deposit about 10 $\mu$m of nickel on the SiC substrate. This is about to be done and will be presented in a future paper.

In summary, the highest etch rate reported to date (1.35 $\mu$m/min) was achieved in a SF$_6$/O$_2$ helicon plasma. This can be attributed to the fact that helicon wave ionization is very efficient and that we minimized the distance between the substrate holder and the source antenna. Smooth etched surfaces free of micromasking have been obtained when using a nickel mask. The selectivity SiC/Ni is about 50 under high etch rate conditions, high enough to make via holes in 4H–SiC substrates (about 300 $\mu$m thick) with a 10 $\mu$m thick nickel mask.

The authors gratefully acknowledge J. Guillou for the design of the new diffusion chamber and movable substrate holder, and D. Thenot for his help during all the experiments.