High Voltage Photoconductive Switches using Semi-Insulating, Vanadium doped 6H-SiC

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Abstract
SiC manufacturers are continually improving the purity of their wafers, however, interband impurities, while detrimental in many applications, can be useful in the operation of photoconductive switches. Compact, high-voltage photoconductive switches were fabricated using c-plane; vanadium doped 6H-SiC obtained from II-VI, Inc. This material incorporates a large amount of interband impurities that are compensated by the vanadium amphoteric, but at present is only available as c-plane wafers. In order to avoid micropipe defects, lateral switches were fabricated to allow validation of material simulations. Low resistivity contacts were formed on the semi-insulating material and a high-voltage encapsulant increases the surface flashover potential of the switch. Material characteristics were determined and switch parameters were simulated with comparisons made to experimental data.

I. INTRODUCTION
Silicon carbide (SiC) is useful as a photoconductive semiconductor switch (PCSS) material due to its wide bandgap and high intrinsic breakdown strength. The high dark (off) resistances required for proper switch operation necessitates the use of semi-insulating (SI) material, which typically has resistivities greater than $1 \times 10^8 \Omega \text{cm}$. In order to produce SI material, manufacturers either have to grow high purity material or dope with an amphoteric, such as vanadium. Vanadium doped material offers some unique advantages in PCSS design. Not only are extremely high resistivities ($1 \times 10^{11} \Omega \text{cm}$) achievable, but there are many inter-band impurities and dopants available for excitation. Presently, vanadium doped material is only available as c-plane material. This requires using a lateral geometry when fabricating switches in order to avoid the micropipe problem[1]. Aside from obvious drawbacks, such as high current densities, lateral switches suffer from low breakdown voltage. Previous experiments have also shown surface current leakage with air to also be a problem. In previous tests, it lowered dark resistance up to three orders of magnitude. These problems can be overcome by using a high voltage encapsulant. This paper presents the results of such a design.

II. MATERIAL CHARACTERIZATION
The switches in these tests were fabricated from wafers from II-VI, Inc. The wafers were supplied with resistivity measurements, but no doping or impurity data. In order to form low-resistance contacts to the material, determination of the materials activation energy and Fermi level was necessary. It is known from the manufacturer that the wafers are vanadium doped with nitrogen and boron as unintentional impurities. It is, however, not known which of the impurities dominates. In vanadium doped SiC, the Fermi level is pinned either to the vanadium acceptor level, located 0.66 - 0.85 eV below the conduction band or to the vanadium donor level, located 1.54 eV below the conduction band[2],[3]. Temperature dependent resistivity tests were carried out between 300 K and 400 K. All tests were done with the switch covered and in the dark in order to avoid any photoexcitation. Overall switch dark resistance vs temperature is shown in Fig. 1. Fluxuations at
low temperature and field are most likely due to an inability to measure such small currents. The Arrhenius equation is typically used to calculate the activation energy and the plot in Fig. 2 was used to determine the activation energy of this sample. The activation energy was determined to be 0.78 eV, which is right in the middle of the range for nitrogen and vanadium doped SiC from literature, but low for recent calculated values[3]. Possible explanations for deviation from the literature are variations of contact resistances with temperature, which is alleviated by various contact-less methods, and inability to accurately take measurements at high dark resistances.

Figure 2. Arrhenius plot of material resistivity vs inverse temperature for the vanadium doped 6H-SiC used in these tests.

**III. SWITCH GEOMETRY AND EXPERIMENTAL SETUP**

Fig. 3a is a diagram of the PCSS used in these tests. The switch is 15 mm x 7 mm and was fabricated on a substrate 385 µm thick with resistivity of 1.2 × 10¹¹ Ω·cm. A 50 nm NiCr (80%-20%) layer was deposited by resistive physical vapor deposition (PVD) and annealed at 1000 °C for 5 minutes to produce ohmic contacts on the SI SiC. NiCr contacts do not exhibit as low of resistivity as Ni contacts, however, they do add mechanical strength to the contact[4] which has proven useful while testing switches in this geometry. Titanium/Platinum/Gold layers were then deposited and the switch was heat treated at 300 °C for 3 hours. The switch was then reflow soldered to a pair of 0.004" copper foils which served as electrodes and points of contact for the exterior circuit. The soldered switch was encapsulated in EFI Polymers, two-part epoxy which had been vacuum degassed to approximately 750 mTorr. The epoxy has a dielectric constant of 3.6 and a dielectric strength of 550 $\frac{V}{\text{mil}}$. The resistivity measurements previously mentioned were performed with this encapsulated system. The encapsulated system was then planarized and polished and switch on resistance tests were performed using the circuit in Fig. 3b.

**IV. RESULTS AND DISCUSSION**

Switch resistance tests were taken at various electric field levels and optical excitation energies. Fig. 4 shows the switch on resistance versus laser energy. All shots were taken using a frequency-doubled (532 nm) Nd:YAG laser. As expected an exponential decrease in switch resistance is seen with increasing laser energy. Fig. 5 shows the decrease in switch resistance with increasing field. Operation at higher electric field levels is advantageous for the PCSS. SiC suffers from low electron mobility (400 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$) compared to other materials used in making PCSSs (1200 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ for GaN, 8500 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ for GaAs). The mobility is even lower in planes parallel to the growth axis. While operating at low fields, electron velocity increases linearly with electric field. These effects can be seen in Fig. 5. However, these increasing electric field levels can lead to other, less desirable, effects which will be shown.

Calculations for minimum theoretical switch on resistance were performed based on material properties and switch dimensions. These theoretical values are shown, along with switch resistance data at low field levels (40 $\text{kV/cm}$), in Fig. 6. This very simplistic model does not take into account quantum efficiency of the switches, which is assumed to be very low. The remainder of the discrepancies between theory and experimental data is most likely due to optical losses from high power densities on the input edge of the switch[5]. Inability to properly align and couple energy from a free space laser into a 400 µm aperture can also lead to a decrease in switch on resistance due to energy...
losses. This comparison highlights the inherent inefficiency of using a high power free space laser as a photoswitch illumination source. These issues are easily resolvable by switching to a fiber optic based delivery system for the exciting laser pulse, which the authors will be transitioning to in future work.

Fig. 7 shows the effects of high field operation on the encapsulated switch. The switch in the image suffered from catastrophic breakdown at approximately 54 \( \frac{kV}{cm} \) after stable operation at approximately 38 \( \frac{kV}{cm} \). Previous high potential tests involving switches with similar geometries and gap distances in the same encapsulant were able to withstand electric field levels of greater than 140 \( \frac{kV}{cm} \) before breakdown occurred. As evidence, in Fig. 7, distortion of the epoxy directly surrounding the switch and copper foils occurred at or before breakdown. Examination of the system has ruled out laser damage as the cause of this distortion. It is believed that high current densities during switching caused thermal expansion and contraction in a region of greatly differing thermal conductivity. Furthermore, the distortion of the encapsulant immediately surrounding the switch is the most likely cause for the, comparatively, low field breakdown of this switch.

V. CONCLUSION

The use of vanadium doped 6H-SiC as a high voltage PCSS material has been demonstrated. The use of lateral switch geometry avoids the micropipe problem in c-plane material. This geometry also takes advantage of the higher mobility perpendicular to the c-plane. The use of high voltage epoxy encapsulant has allowed the operation of these switches up to field levels of 140 \( \frac{kV}{cm} \), however,
without a way to efficiently remove heat generated by the system operating field levels are greatly decreased because the integrity of the epoxy quickly degrades.

VI. REFERENCES


