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HIGH ELECTRIC FIELD, HIGH CURRENT PACKAGING OF SIC PHOTO-SWITCHES*

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Abstract

This paper discusses the methods and materials being developed to package semi-insulating Silicon Carbide (SiC) in a high electric field, high current package while providing entrance for photo-conductive optical energy necessary for closure. The switch requirements and design goals are presented. The switch material package combination must enable a relatively large current and control the current density at the contacts and through the material while supporting a very high electric blocking field. The material parameters and methods of controlling the current density and the peak electric field in the region where the electrode separated from the SiC material are discussed. The mask design and Ohmic contact formation processes at the SiC – metal electrode interface as well as the methods used to bond the semiconductor contact to the electrode are discussed. In addition, images of package failures are presented and the direction being pursued for improving package performance is presented.

I. Extrinsic, Linear SiC Photo-Switch

Semi-insulating Silicon Carbide (SiC) is being employed in a linear, extrinsic, photo-conductive [1 switch mode in the geometry shown in Fig. 1. The extrinsic mode, in which the optical closure photon energy is less than the band gap energy, is being used to control the optical absorption depth and the current density, which is dependent upon the interband dopant densities.

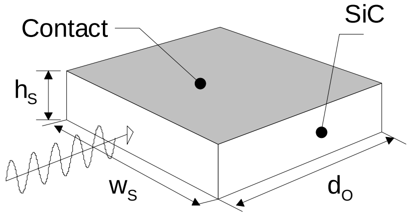

Figure 1. Extrinsic SiC Photo-switch Geometry

Semi-insulating SiC has a very large resistivity due to near perfect compensation of the defect and impurity acceptors. One 6H-SiC compensation structure employs Vanadium to compensate the residual density of Nitrogen. Careful growth procedures can result in resistivities of over 10^{15} Ohm-cm, which correspond to a free electron density at room temperature of only 10^8 electrons per cubic centimeter.

The extrinsic mode of operation results in an effective optical absorption depth, d_O, illustrated in Fig. 1 that is dependent upon the interband dopant densities, both acceptors and donor elements. The switch blocking voltage is dependent upon the dielectric strength of the switch, which for SiC is on the order of 3 MV/m, and the height of the switch between electrodes, h_S , in Fig. 1.

II. High Voltage, High Current Package

The maximum current density of the material is determined by the density of available donors and acceptors that can be activated by the absorbed optical energy. This current density is conducted to the external circuit by the area of electrode in contact with the SiC material. The electrode geometry that interfaces the SiC material must be compatible with high electric field operation. These two requirements have been combined

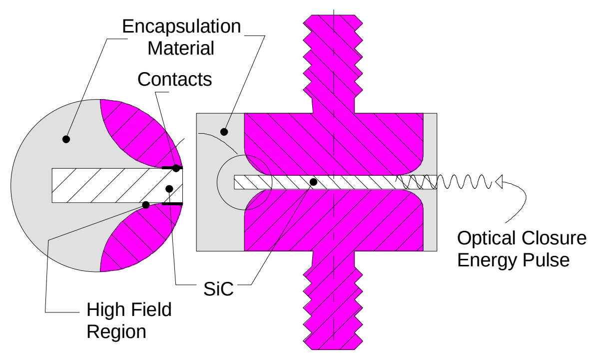

Figure 2. High Voltage, High Current Geometry

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into the practical SiC switch geometry illustrated in Fig. 2 that also illustrates the port for injection of optical energy into the switch material.

The SiC region between the electrodes is exposed to the highest electric field that is supported by the bulk material. In the circled region of Fig. 2, where the conducting electrode separates from the SiC surface, the electric field is enhanced by the electrode curvature and the medium between the SiC and the electrode is subject to a very large electric fields.

Note also in Fig. 2, the location at which the optical energy is injected into the switch. The optical absorption depth must be much larger than the electrode diameter in order to optically produce holes and electrons between the electrodes. The design of the location for optical injection is a trade off between high voltage tracking around the SiC crystal and the volume of SiC material that will absorb optical energy outside the intimate electrode contact region.

III. Switch Voltage Testing

Several switches were fabricated and exercised in the pulse circuit of Fig. 3. A repetitive pulse was applied to

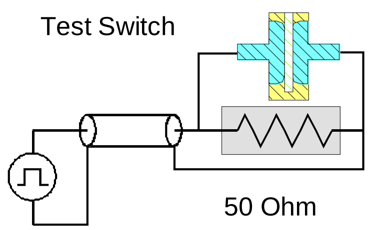

Figure 3. Pulse Charge Switch Voltage Circuit

the test switch in parallel with a 50-Ohm resistance at the end of a coaxial cable. The voltage across the switch and the current through the switch and 50 Ohm resistance are shown in the two sets of waveforms of Fig. 4. The

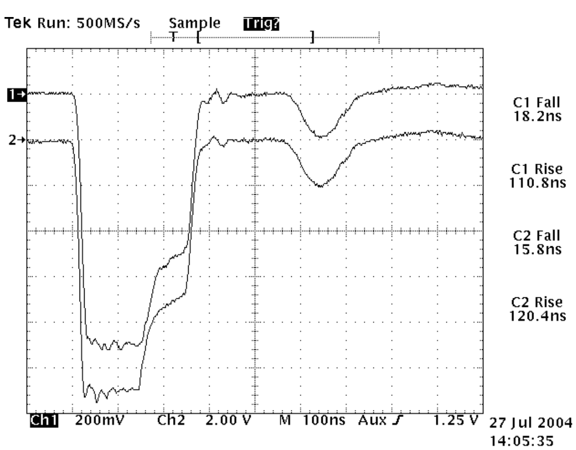

Figure 4. Pulsed Switch Voltage Waveforms

switches were pulsed without external optical input to determine the voltage blocking parameters. During the pulse of Fig. 4, a capacitive coupled discharge occurred across the end of the input surface. The decrease in switch voltage during the pulse is thought to be due to the optical energy from the arc discharge at the edge of the SiC. The switch dark resistance is approximately 100 M-Ohms and the required optical energy to drop the switch resistance is only several tens of pico Joules as calculated in TABLE 1.

TABLE 1
Pulse Charge Switch Parameters

Parameter	Symbol	Value	Unit
Switch Dark Resistance	Rd	1.00E+08	Ohm
Electrode diameter	ds	8.00E-03	m
Electrode area	As	5.02E-05	m^2
SiC thickness	hs	4.00E-04	m
Dark Resistivity	ρd	1.26E+07	Ohm-m
Mobility	μ	60	M^2/V-s
electron charge	qe	1.60E-19	C
Dark electron density n-type	ned	8.29E+09	$1/m^3$
Switch Conductivity			
Ratio Ro/Rs		0.64	
Load Resistance	RL	50	Ohm
Switch Conduction Resistance	Rsc	87.5	Ohm
Assumed Wavelength	λ	5.32E-07	m
Planck's constant	h	6.63E-34	J-s
Vacuum speed of Light	co	3.00E+08	m/s
Optical Frequency	fo	5.64E+14	Hz
Photon Energy	Eλ	3.74E-19	J
Optical Energy Required	Eoa	7.12E-11	J

IV. Switch Voltage Breakdown

The switch that produced the waveforms of Fig. 4, failed and the structure was dismantled to locate the fault. Several pictures that are displayed in the following figures point to a failure at the edge of the intimate electrode contact area. Further examination pointed to several fabrication problems, including:

1) Faulty alignment of the Ohmic contact or the electrode on the opposing sides of the SiC substrate.
2) Incomplete encapsulation with the insulating material in the high field region
3) Ragged solder protrusions from the bonding process in the high electric field region

4) Incomplete bonding at the surface interface that result in field enhancement points

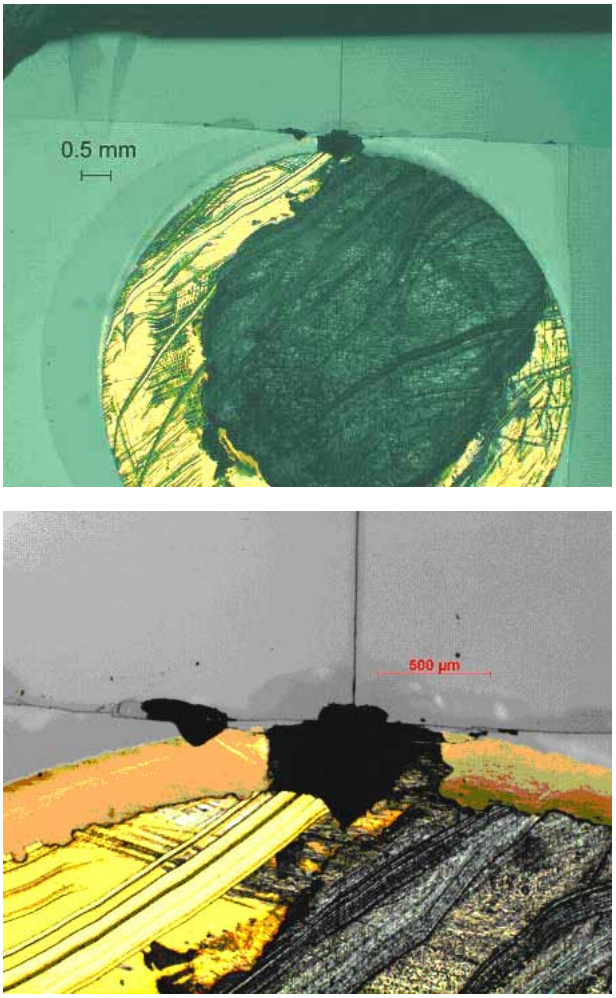

Figure 5. Switch Failure point at electrode edge

V. Summary

The preliminary results indicate that a respectable area (~0.5 cm^2) of the SiC substrate employed can support appreciable electric fields (~300 kV/cm) without affects due to micropipes and stacking defects. Dielectric strength failure of the switch material and package at this level appears to be due to electric field enhancements at the edge of the electrodes. The optical activity of the switch is demonstrated by the self-illumination due to transient discharge at the edge of the SiC substrate. The fabrication techniques that led to the failures appear to be related to insufficient alignment accuracy, incomplete encapsulation, and incomplete bonding techniques. Therefore, the path to be taken involves developing all of the fabrication, bonding, and encapsulation techniques.

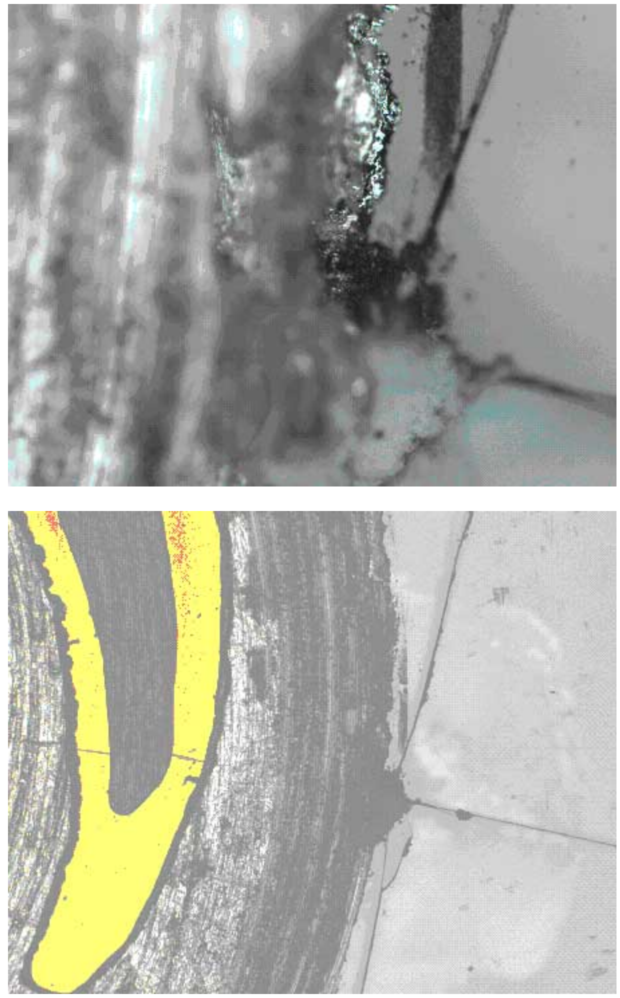

Figure 6. Switch Failure point at electrode edge

VI. References

[1] W. C. Nunnally and M. Mazzola, “Opportunities for employing silicon carbide in high power photo-switches,” Proceedings of the IEEE Pulsed Power Conference, Dallas, TX, 2003.