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Opportunities for Employing Silicon Carbide in High Power Photo-Switches

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Abstract

High electric field geometries for high power, photo-conductive switches made possible by employing sub-bandgap energy photons and inter-bandgap dopants / defects are being investigated for compact pulse power systems. The high field, long absorption depth package reduces the required linear mode, optical closure energy and also reduces the conduction current density through the active material and at the contacts. This paper describes the opportunities for employing semi-insulating SiC wafer in the University of Missouri-Columbia, high electric field configuration. The parameters of semi-insulating SiC materials and methods of fabricating such materials into a high power photo-switch are discussed. , In addition, transient modeling of the transverse injection of optical closure energy is discussed.

I. INTRODUCTION

A new candidate for the active photo-conductive material in high field photo-switches is semi-insulating SiC. Two examples are vanadium compensated SiC (V:SiC) and intrinsic SiC with very low impurities. Semi-insulating SiC is compensated in much the same manner as semi-insulating GaAs in that the bandgap structure has a number of intergap energy levels that can be controlled during the growth process and that determine the optical absorption depth for photon energy less than the band gap. In V:SiC, V forms two deep levels, an acceptor at E_c - 0.97 eV and a donor at E_c - 1.6eV (4H-SiC) [1-3]. In intrinsic, semi-insulating SiC the defect energy levels below the conduction band are in the center of the band such that absorption depths of several tens of mm at the appropriate activation wavelength can be obtained [4,5]. These characteristics make this material suitable for large area photoconductive switches utilizing extrinsic photoconductivity.

II. BACKGROUND

The University of Missouri-Columbia (UMC) is developing, linear, high electric field, photo-conductive switch technology by employing extrinsic photo-conductivity to control the optical absorption depth and thus the switch current density. The active photo-conductor material is placed in the high electric field geometry shown in Fig. 1. The electric field is shaped using high permittivity materials in the region where the switch electrodes separate from the active material. The UMC high permittivity package reduces the electric field at the edge of the semiconductor discs to increase the package voltage.

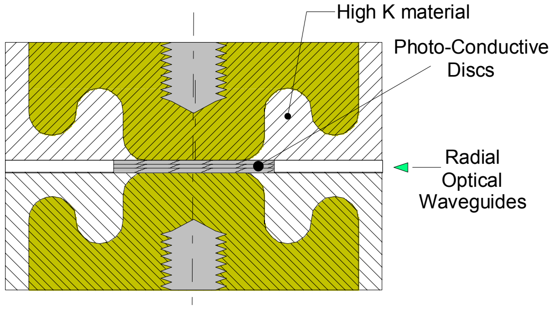
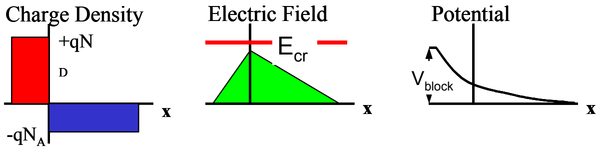
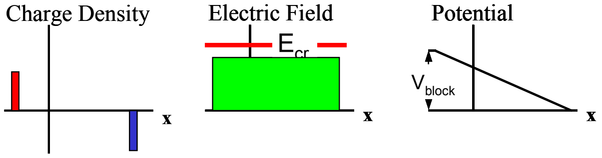


Figure 1. UMC Photo-Conductive Switch Package

Photo-conductive switches sustain or block the applied voltage prior to controlled closure due to the semi-insulating conductivity of the bulk material rather



a) pn Junction Switch



b) Bulk Photo-Conductive Switch

Figure 2. Comparison of Switch Blocking Voltage

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than space-charge depletion at a pn junction as compared in Fig. 2. Note that the peak electric field in the bulk photo-switch (ideally, equal to the average field) is much lower than the peak field in a pn junction. Thus, when only the active material is considered, the bulk photo-switch will support a larger voltage than a pn-junction switch with the same material dielectric strength. The major limitation in voltage is presently not the material, but the package and thus the package is the focus of the UMC work.

In concurrent work with Gallium Arsenide (GaAs), multiple layers of semi-insulating, photo-conductive material are bonded in series to form the switch working volume. In GaAs, heavily doped, n^+ layers at the negative electrode are used to reduce electron injection which prevents electron avalanche which would close the switch. In the UMC geometry, n^+ layers are deposited on each layer of GaAs to further intercept incipient electron avalanches. This investigation continues.

The thickness or height, h_S, of the active switch region is given by

$$h_s = \frac{V_b}{E_{op}} = \frac{2 \cdot V_b}{E_{\max}} \tag{1}$$

where V_b is the switch blocking voltage, E_{OP} is the operating electric field which is half of the maximum electric field, E_{MAX}.

The first order optical closure energy, O_E is also critically dependent on the height of the switch or

$$O_E = \frac{E_\lambda \cdot h_s^2}{R_c \cdot q_e \cdot \mu_s} \tag{2}$$

where E_λ is the photon energy, R_C is the conduction resistance, q_e is the electron charge, and μ_S is the sum of the electron and hole mobility. The above equation indicates the benefits of operating the switch at high electric fields. The conduction voltage drop across the switch determines the dissipation of the switch. If the switch is to be 95% efficient implying that the conduction voltage, V_C , is 5 % of the blocking voltage, V_B, such that the conduction electric field , E_C is given by

$$E_c = \frac{V_c}{h_s} \tag{3}$$

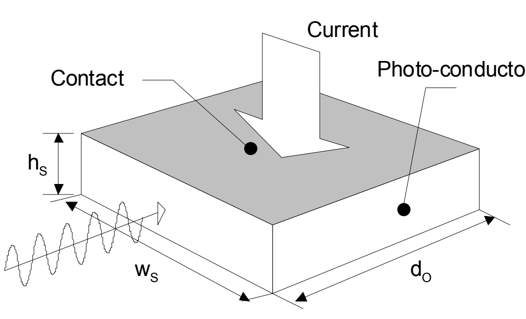

Figure 3. Photo-Switch Conduction Geometry

For the conduction geometry shown in Fig. 3, the average current density is determined by the optically generated carrier density, n_C, and the optical absorption depth, d_O, or

$$J_d = n_c \cdot q_e \cdot \mu_s \cdot E_c = \frac{I_S}{w_s \cdot d_o} \tag{4}$$

where E_C is the conduction electric field, I_S is the switch current and w_S is the illuminated width of the switch. Note that the optical absorption depth and the carrier density are related.

In an extrinsic photo-conductor, the electrons elevated to the conduction band are sourced from defects and donor levels within the bandgap. The band structures for typical semi-insulating GaAs and SiC, with the major deep energy levels, are illustrated in Fig. 4. Note that the band gap for SiC is approximately 2.3 times that of GaAs. In the case of GaAs, a photon wavelength of one micron (~ 1.2 eV) will elevate the donor level electrons to the conduction band. In the case of SiC, a photon wavelength of 0.5 micron (~2.4 eV) will elevate the electrons donated by the defect and donor levels to the conduction band.

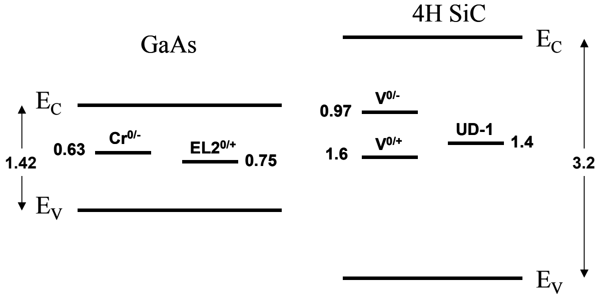

Figure 4. Band Structure for GaAs and 4H-SiC

If the sum of the optically available donor defect density is N_D, the optical absorption efficiency is η_A, and the optical control source is sufficiently powerful to provide sufficient photon density to ionize all available defect/donor sites, the spatial, optically produced carrier density can be approximated by

$$n_c(x) \approx N_D \cdot \eta_A \cdot e^{-\alpha \cdot x} \tag{5}$$

where α is the optical absorption coefficient of the material at the control wavelength. Therefore, the effective conducting area of the switch is determined by the optically generated carrier density and thus the optical absorption depth.

III. Photo-Switch Materials

Semi-insulating GaAs has been employed as a photo-switch material due to its availability, high electron mobility, and large dark resistivity. The potentially large mobility reduces the optical energy requirements necessary to produce a given conduction resistance. In addition, the large dark resistivity is essential to minimize resistive dissipation during voltage application. More importantly, GaAs materials can be triggered into conduction through optical seeding of avalanche processes that reduce the optical closure energy by three to four orders of magnitude. However, the related filamentary conduction has been shown to damage the bulk photo-conductive material and high current densities at the contact limit the power handling capability of these avalanche photo-switches.

Evolving silicon carbide material developments have made semi-insulating SiC an attractive photo-conductive switch material. The parameters for 4H-SiC are compared with GaAs in TABLE I.

TABLE I. GaAs and SiC Material Properties

Parameter	GaAs	4H-SiC	Unit
Band Gap	1.43	3.26	eV
Electron Mobility @ 3 kV/cm	6000	60	cm^2/V-s
Electron Mobility @ 10 kV/cm	1000	300	cm^2/V-s
Max E-Field	250	3000	kV/cm
Dark Resistivity	10^7	10^{11}	Ohm-cm
Max Drift Velocity	$2\text{x}10^7$	10^7	cm/s
Recombination time	0.5	200-800	ns
Thermal Conductivity	0.55	4.9	W/cm-K

Note from TABLE I the large difference in maximum electric field that the materials will support. SiC is 12 times larger than GaAs. Also note that the mobility of GaAs at a conduction electric field of 3 kV/cm is 20 times greater than SiC at a conduction electric field of 10 kV/cm. The electron drift velocity versus electric field for GaAs and SiC are illustrated in Fig. 5. These parameters affect the conduction voltage drop and the power dissipated in the switch as well as the optical closure energy requirements.

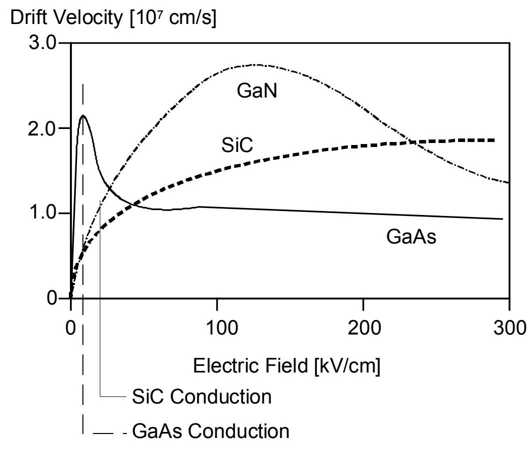

Figure 5. Material Drift Velocity vs Electric Field

Consider a comparison between a GaAs switch and a SiC switch. Assume that the operating electric field of a SiC is only 6 times greater than that of GaAs. This assumption is appropriate since the thickness of the SiC will be 1/6 that of GaAs so that during conduction, the SiC switch will have a similar conduction voltage, but a larger conduction electric field. In addition, the conduction mobility of GaAs is 6 times that of SiC. Therefore the conduction resistance of a SiC switch and a GaAs switch are as follows

$$R_{C-GA} = \frac{E_\lambda \cdot {h_{s-GA}}^2}{\mu_{e-GA} \cdot q_e \cdot E_{o-GA}} \tag{6}$$

and

$$R_{C-SC} = \frac{E_\lambda \cdot {h_{s-SC}}^2}{\mu_{e-SC} \cdot q_e \cdot E_{o-SC}} \tag{7}$$

such that the ratio of optical control energies that result in the same conduction resistance using the same photon energy is given by

$$\frac{{h_{s-GA}}^2}{\mu_{e-GA} \cdot E_{o-GA}} = \frac{{h_{s-SC}}^2}{\mu_{e-SC} \cdot E_{o-SC}} \tag{8}$$

$$\begin{aligned} \frac{E_{o-SC}}{E_{o-GA}} &= \left(\frac{h_{s-SC}}{h_{s-GA}}\right)^2 \cdot \left(\frac{\mu_{e-GA}}{\mu_{e-SC}}\right) \\ &= \left(\frac{E_{B-GA}}{E_{B-SC}}\right)^2 \cdot \left(\frac{\mu_{e-GA}}{\mu_{e-SC}}\right) \approx 0.16 \end{aligned} \tag{9}$$

This result indicates that only 16% of the optical energy is necessary to produce the same conduction resistance as in the GaAs switch. Conversely, the same optical energy will produce a conduction resistance that is 16% of that in the GaAs switch. The mobility estimates probably make these conclusions conservative.

The dark resistivity of GaAs is approximately 4 orders of magnitude lower than that of semi-insulating SiC and thus the “off” state power dissipation of a SiC switch is reduced by the same factor.

Another major advantage of the SiC, an indirect band semiconductor, is that the recombination time of SiC is over 400 times larger than that of GaAs. Photo-conductively produced carriers recombine in the absence of additional optical energy with the characteristic material recombination time. In order to maintain the initial conduction resistance, additional optical energy must be injected into the switch to replace the carriers lost to recombination. In steady state, the carrier generation rate is equal to the rate carriers are lost to recombination or

$$\frac{dn_{SS}}{dt} = 0 = \frac{P_{L-SS}}{E_\lambda \cdot h_S \cdot d_O \cdot w_S} - \frac{n_{SS}}{\tau_R} \tag{10}$$

where n_{SS} is the steady state carrier density, $P_{L\text{-}SS}$ is the steady state optical power and τ_R is the material recombination time. Thus, the steady state optical power, $P_{L\text{-}SS}$ is inversely proportional to the recombination time or

$$P_{L-SS} = \frac{n_{SS} \cdot E_\lambda \cdot h_S \cdot d_O \cdot w_S}{\tau_R}. \qquad (11)$$

In this comparison, the optical power required to maintain conduction in a SiC switch is over 400 times less than that required for the GaAs switch.

The design and comparison of a GaAs photo-switch and a SiC photo-switch, illustrated in TABLE II, point out the advantages of employing SiC. The designs in TABLE II assume a quantum absorption efficiency of unity, a lossless optical transfer of optical energy into the conduction region, and a switch conduction area of 1 cm x 1 cm.. The depth of the conduction region is determined by the optical absorption depth that is assumed to be 1 cm.

TABLE II

Parameter	GaAs	4H-SiC	Unit
Blocking Voltage	1.00E+04	1.00E+04	V
Blocking Electric Field Max	1.00E+05	5.00E+05	V/cm
Bulk material thickness	1.00	0.20	mm
	0.1	0.02	cm
Conduction Electric field	3.00E+03	1.00E+04	V/cm
Conduction electron mobility	6.00E+03	3.00E+02	cm2/V-s
Photo Carrier Density	1.00E+15	5.00E+15	cm-3
Conduction Current Density	2880.00	2400.00	A/cm2
Conduction Voltage	300.00	200.00	V
Conduction Impedance	0.104	0.083	Ohm - cm2
Wavelength	1.06E-06	5.32E-07	m
Photon Energy	1.87E-19	3.74E-19	J
Optical Closure Energy	1.87E-04	1.87E-03	J/cm3
Prototype 1 square cm switch			
Switch height	1.00E-01	2.00E-02	cm
Switch width	1	1	cm
Optical Absorption Depth	1	1	cm
Conductivity	9.60E-01	2.40E-01	mho/cm
Conduction Resistance	1.04E-01	8.33E-02	Ohm

IV. Summary

The first order comparison in TABLE II indicates a 1 square cm conduction area can conduct ~ 2.5 kA with a conduction drop of 200-300 Volts while blocking 10 kV. These parameters indicate a voltage switching efficiency of 97.5 percent, assuming the source and load impedance are appropriately matched.

Note from the previous comparable designs, the current density in SiC can be similar to that in GaAs, even though the mobility of SiC is only 1/20 ~~th~~ of GaAs. Furthermore, the conduction voltage drop in a SiC switch is essentially the same as a GaAs switch when the SiC is operated at a larger conduction electric field. Thus, the advantages of the SiC switch are made possible by operating the SiC material at high blocking electric field, which justifies the focus on the development of ~~a~~ high electric field packaging. In addition, the order of magnitude larger thermal conductivity of SiC as compared to GaAs enables higher average power operation with SiC.

The most important part of the present research is the development of the high electric field photo-switch packaging technologies and methods of efficiently delivering the optical closure energy to the conducting region. Presently, experimental determination of the extrinsic optical absorption and quantum efficiency properties of the SiC materials remains to be measured. In addition, methods of efficiencly introduding the optical control energy to the switch are another research task that is being pursued.

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