

6H SILICON CARBIDE PHOTOCONDUCTIVE SWITCHES FOR HIGH POWER APPLICATIONS

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ABSTRACT

High voltage, high current, low inductance, fast resistive transition, precisely controlled switches are the critical component that can enable fielding the most compact pulse power systems. Presently, the only known switch technology with the potential to fulfill these requirements is photo-conductive switching of bulk semiconductors. This document discusses the additional developments of extrinsic, semi-insulating, Silicon Carbide, photo-conductive switches that are required to bring the photo-SIC switch to technology readiness level 4 or 5. The basic physics rationale for employing extrinsic photo-conductivity has been demonstrated through modeling and first order experiments. The current hurdle is package and base device fabrication followed by increasing the conduction time beyond the material recombination time.

The proposed work will investigate methods of extending the structure blocking voltage and the package dependent voltage to a larger fraction of the bulk material dielectric strength (3 MV/cm) and extending the switch conduction time to many times the material recombination time which reduces the optical control energy required for efficient operation.

1. COMPACT PULSE POWER SYSTEMS

Previous work (Nunnally, 2004)¹ at the University of Missouri – Columbia (UMC) has identified

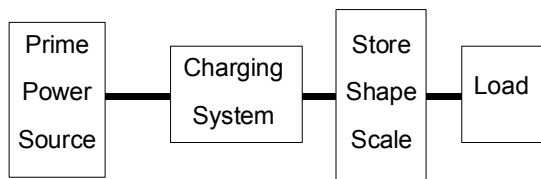


Figure 1. Compact Pulse Source Architecture

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the most compact pulsed generation architecture as one in which the functions of energy storage, current and voltage scaling and pulse shaping are embodied in the same volume as illustrated in Fig. 1. Note that the most compact system is one in which the entire volume is consumed by the energy storage unit and thus the minimum volume for a system is the volume of the energy storage dielectric. One such configuration that

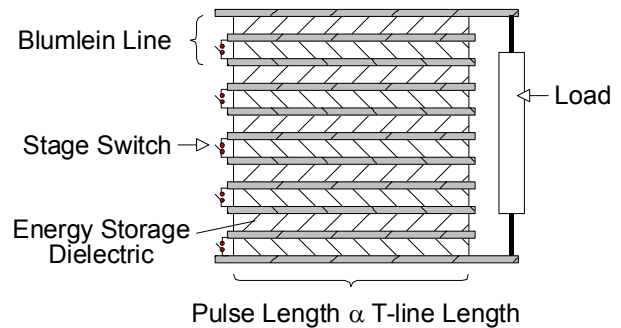


Figure 2. Stacked Blumlein Line Pulse System

results in the most compact pulse power system is the Stacked Blumlein Line (SBL) System, illustrated in Fig. 2, in which the energy density of the system can approach 30 – 60 % of the energy density of the dielectric when the auxiliary subsystems, such as charging and triggering subsystems, are taken into account. The SBL system can be designed to match any load impedance. The output voltage is determined by the number of Blumlein lines in the stack, the output current is proportional to the width of the transmission lines, and the output pulse length is proportional to the length of the transmission lines.

The basic module of the SBL is a single Blumlein line, consisting of two transmission line sections and a switch, as illustrated in Fig. 3. The single Blumlein, when connected to a load that is equal to the sum of the two transmission line sections, charged to V_C and the ideal switch is closed, generates a square pulse in the load with a period equal to the two way transit time of a transmission line section with an amplitude equal to the charge voltage as illustrated by the waveform of Fig. 3.

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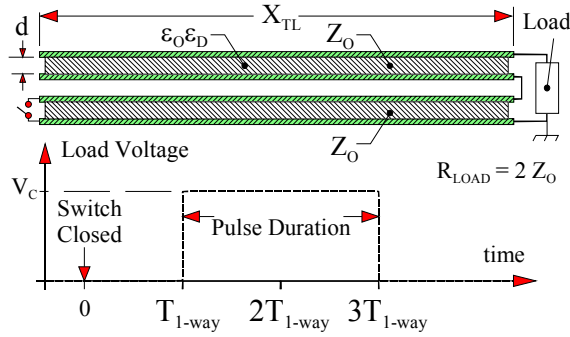


Figure 2. Basic Blumlein Operation

Therefore, the length of the transmission line sections, X_{TL} , and the relative dielectric constant of the transmission line dielectric, ϵ_D , determine the pulse length. The thickness of the dielectric, d , is determined by the dielectric strength and the charge voltage, and the width of the transmission line determines the impedance of the transmission line, Z_0 . The energy delivered to the load is equal to the energy stored in the dielectric divided by the fraction of the volume occupied by the transmission line conductors², neglecting the volume associated with the switches and the switch control system. Therefore, the volume of the SBL approaches the absolute minimum system volume of the energy storage dielectric, which is the most compact system possible. The density of energy storage in a real system can be about 25-33% of the maximum possible, the energy stored in the dielectric¹ when the auxiliary systems are included.

The most interesting feature of SBL systems is that a module consisting of a single Blumlein Line can be used in series-parallel combinations to obtain nearly any desired output, if the switches can be precisely controlled and closed simultaneously. For example, multiple single Blumlein modules can be stacked to obtain the desired pulse voltage and/or paralleled to obtain the desired current.

The previous work identified the critical parameters of the stage switches which are the enabling technology for compact pulse power systems as:

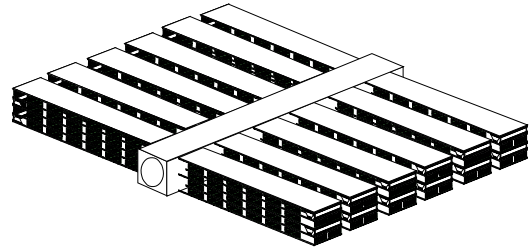
- Large blocking electric field
- Large current densities
- Low Inductance
- Small resistive transition times
- Precise closure time control
- Optical switch control desirable
- High voltage trigger isolation

The SBL system, as illustrated in Fig. 4, can be applied in numerous applications, and configurations which require compact, high power pulse sources such as electric discharge lasers, high power microwave sources, high current, electron beam accelerator drivers, and essentially all directed energy systems.

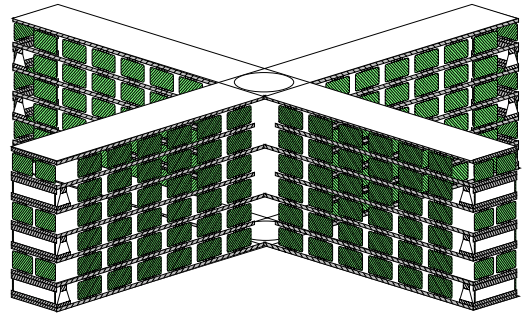
The previous work also developed the design rules for SBLs (Nunnally, 2006³) that are listed in TABLE 1.

TABLE 1: SBL Stage Design Rules

Parameter	Value Equation
Load Impedance	Z_L
Load Voltage	V_L
Load Current	$I_L = V_L/Z_L$
Pulse Risettime	T_{rise}
SBL Output Impedance	$Z_B = Z_L$
Blumlein Stage Voltage	V_S
Number of Series Blumleins in SBL	$N_B = V_L/V_S$
Blumlein Stage Impedance	$Z_S = Z_B/N_B$
Stage Switch Parameters	
Switch inductance	$L_S < (T_{rise} Z_S)/10$
Switch Resistive Transition time	$T_{rise}/10$
Switch voltage	V_S
Switch Current	$2I_L$
Switch Closure variation (Jitter)	$T_J = T_{rise}/20$



Electric Discharge Laser



High Current Accelerator

Figure 4. Illustration of SBL Applications

The only known technology that presently has the potential to provide the critical parameters above are photo-conductive semiconductor switches. Additional work by the UMC Photonics for Radar and Optical Systems (PROS) group has demonstrated that the relatively new material of Vanadium compensated, semi-insulating Silicon Carbide (V:SiC) operated in the

extrinsic photo-conductive mode is the leading candidate for photo-conductive switch.

2. SILICON CARBIDE PHOTO-CONDUCTIVE SBL STAGE SWITCHES

Previous work (Kelkar, et al, 2005⁴, Gunda, et al. 2005⁵, Nunnally, et al, 2003⁶) has demonstrated the viability of Vanadium compensated, semi-insulating,

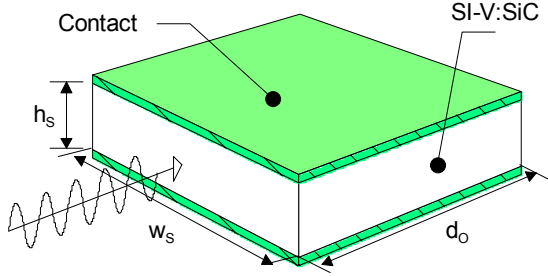


Figure 5. Extrinsic Photo Conductive Switch

extrinsic Silicon Carbide (SiC) switches in high power applications. The UMC approach, illustrated in Fig. 5, employs extrinsic photo conductivity in which the density of interband dopants determines the optical absorption depth and thus current density due to optical absorption.

Silicon Carbide, with its very large dielectric strength of 3 MV/cm, enables the switch to be designed with thicknesses determined by

$$h_s = \frac{V_B}{E_S} \quad (1)$$

where V_B is the switch blocking voltage and E_S is the switch material dielectric strength. The small values of h_s enable switches to be designed with practical optical closure pulse energies, E_O , given ideally by

$$E_O = \frac{E_\lambda \cdot h_s^2}{q_e \cdot \mu_s \cdot R_C} \quad (2)$$

where q_e is the electron charge, μ_s is the sum of the mobilities in the switch material, R_C is the conduction resistance, and E_λ is the energy of the optical photon.

The difference between extrinsic photo conductive switches and intrinsic photo-conductive switches is illustrated in Fig. 6. The absorption of optical energy produces free carriers, holes plus electrons, in the switch which, along with the carrier mobilities, determines the conduction current density. The effective optical absorption depth and thus the maximum current density in extrinsic photo-conductive switches are determined by the un-ionized dopant densities at energies greater than the extrinsic Fermi level that absorb optical energy. Note that the carrier mobilities of SiC are low compared to other semiconductors. However, the small switch material thicknesses between electrodes results in similar conduction resistances. In addition, the extrinsic

mode of operation also limits the switch conduction current density since once all the interband dopants have

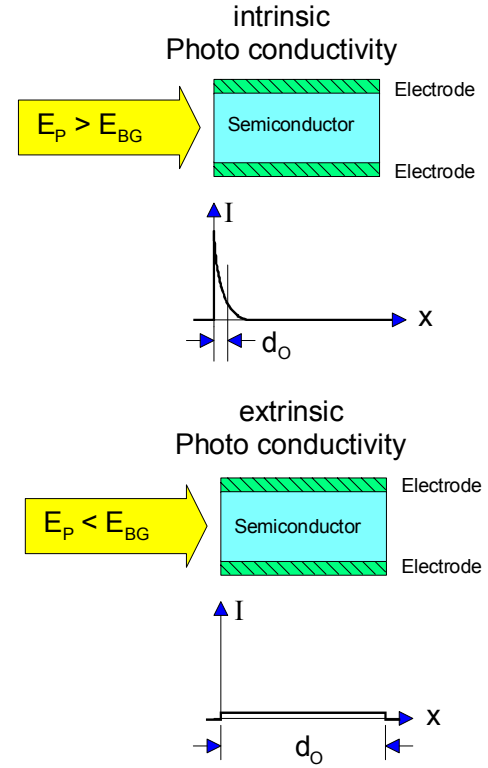


Figure 6. Extrinsic vs. Intrinsic Photo-conductive

been excited by the absorbed optical energy, no additional current carriers are available and the current density has an upper limit which facilitates contact lifetime and bulk material lifetime. The recently available, semi-insulating SiC materials, specifically Vanadium compensated are an ideal host for extrinsic photo conductive dopants.

A major portion of the work conducted in the compact pulse power system project is the investigation, identification and modeling of the compensation structures, illustrated in Fig. 7, that result in semi-insulating SiC. Note that compensation produces semi-insulating material, not by removing all impurities as intrinsic materials, but by adjusting the acceptor and donor densities in such a manner that they cancel leaving only a very small density of free current carriers in the semiconductor material. It is also important that the compensating element have energy levels near the center of the band structure to pin the extrinsic Fermi level near the center of the band gap.

In semi-insulating SiC, Nitrogen and Boron are the common dopants in the material that can be compensated by adding Vanadium, which has donor and acceptor levels near the mid band in SiC. The UMC work confirmed the two compensation structures that are based on energy levels in 6H-SiC (Bickermann, et al. ,

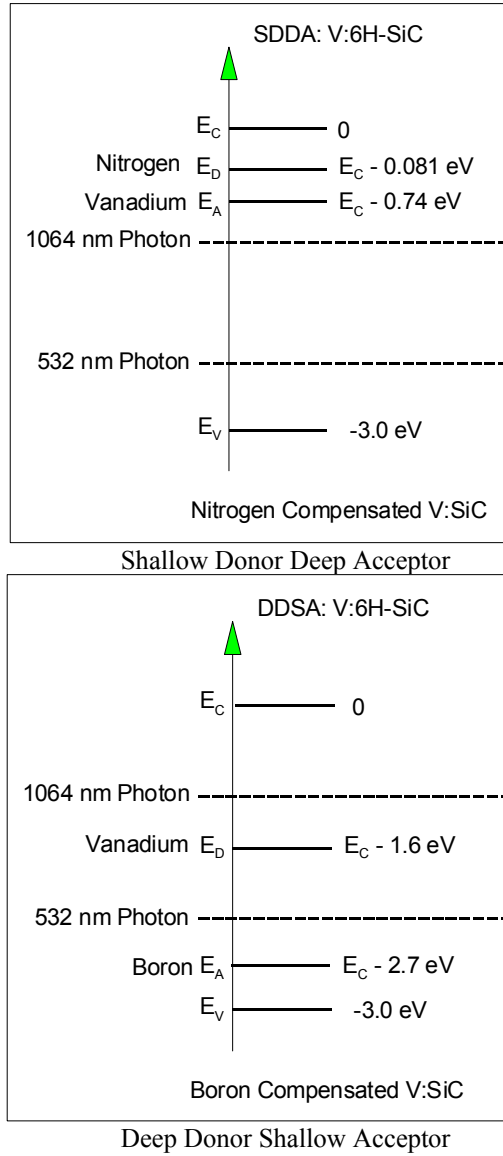


Figure 7. Vanadium Compensation Structures in Silicon Carbide

2003⁷⁾ specifically noted as (1) Deep Donor Shallow Acceptor (DDSA) and (2) Shallow Donor Deep Acceptor (SDDA) that are illustrated in Fig. 7. Note in the band energy plots of Fig. 7 that the photon energies at 1064 nm and 532 nm are also indicated which illustrates the donors and acceptors that are available for photo excitation.

Detailed semiconductor physics simulations have determined the recombination time of these materials differ markedly such that the materials can be designed for specific applications. The simulation of the temporal behavior of the carrier density is illustrated in Fig. 8, which indicates the DDSA material, as modeled, has a much smaller recombination time than the SDDA material. In reality, the effective recombination time is a function of the densities of the individual dopants and their position in the band.

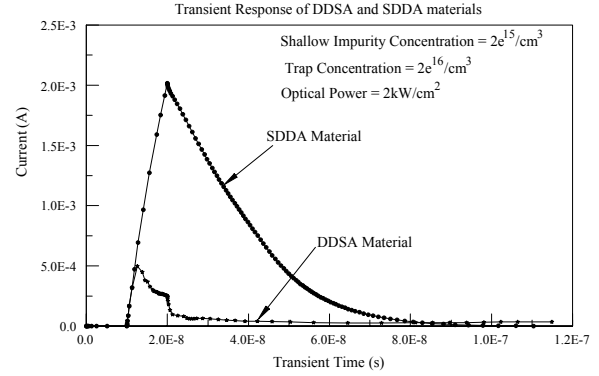


Figure 8 Current density Recombination Time of Two Compensation Structures

Note that Vanadium compensated, SiC has similar properties to those of semi-insulating GaAs. The materials are trap dominated, that is, the characteristics of the material are determined by the densities and recombination cross sections of the interband traps, donors, and acceptors.

3. HIGH VOLTAGE, HIGH CURRENT, PACKAGE

A major focus of the UMC work is the design and initial development of a switch package that is compatible with high voltages, high currents, optical access to the switching material, and compatible with deployment in real world applications. The required inductance of the photoconductive switch in the SBLs described above is a function of geometry and the impedance of the transmission line. For example, the inductance required to switch a flat plate SBL, as illustrated in Fig. 8, and produce a fast risetime, the inductance must be low. The inductance of the geometry illustrated in Fig. 8 is approximately

$$L_{SW} = \frac{\mu_0 \cdot x \cdot d}{w} \quad (3)$$

where the dimensions are illustrated in Fig. 9 and μ_0 is the permeability of free space. Thus for minimum or low

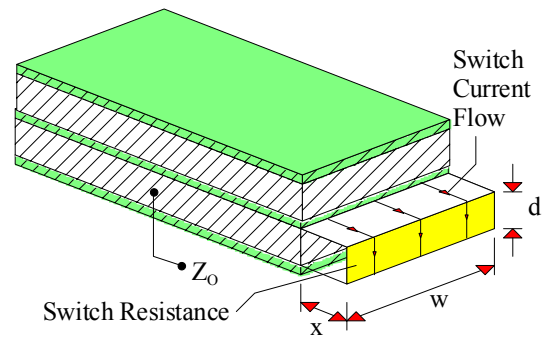


Figure 9. Low Inductance SBL Switch Geometry

inductance, the width of the current conduction path should be as large as possible and the area enclosed by the current flow should be as small as possible. Figure 9 points out two critical advantages of linear photoconductive switches. The conduction resistance of a photoconductive switch is independent of width, see Eq. 2, and only dependent upon the absorbed optical energy. Secondly, the conduction current flows in the switch only where the controlling optical energy is injected. Thus if the optical energy is injected across the width of the Blumlein Line switch, the current will flow across the width which yields the minimum inductance possible.

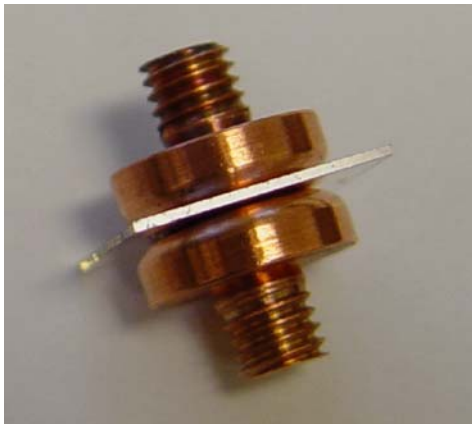
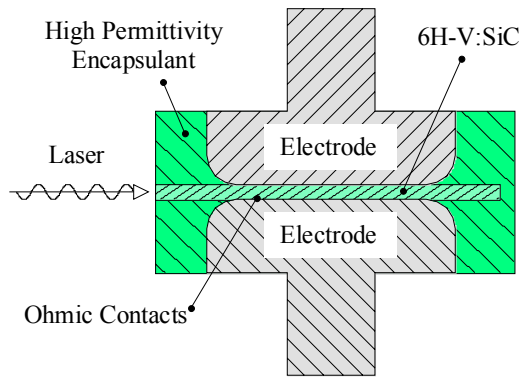


Fig 10. Basic UMC switch geometry

For research, development and cost purposes, a smaller SiC, illustrated in Fig. 10, was fabricated at the Lawrence Livermore National Laboratory, using A-plane (surfaces parallel to micropipe growth direction) semi-insulating 6H-V:SiC, as illustrated in Fig. 10.

A SiC slab is cleaved into a square chip 400 microns thick to allow optical energy injection through the cleaved face. Ohmic contacts were aligned and fabricated on opposite sides of the SiC slab using the common Nickel Silicide process followed with subsequent deposition of multiple metallic layers to form the slab-electrode interface. The large Copper electrode is soldered to the

Gold top contact layer using Indium solder to form the bare switch, also shown in Fig. 10. The initial switches used clear epoxy to manage the enhanced electric field stress in the region where the electrode departs the surface of the SiC for operation at relatively low voltages. The second version of the switch package employed high permittivity, nano-particle dielectrics (Nunnally et. al, 002) ⁸ in the electrode edge-slab region to further manage the electric field enhancement. Both of these packages have limited operating voltages due to high fields in the region where the electrode departs from the semiconductor surface and inherent physics limitations that are to be addressed in the proposed work.

The ongoing effort to design the switch package for operating voltages that are worthy of the SiC dielectric strength are focused on the development of additional

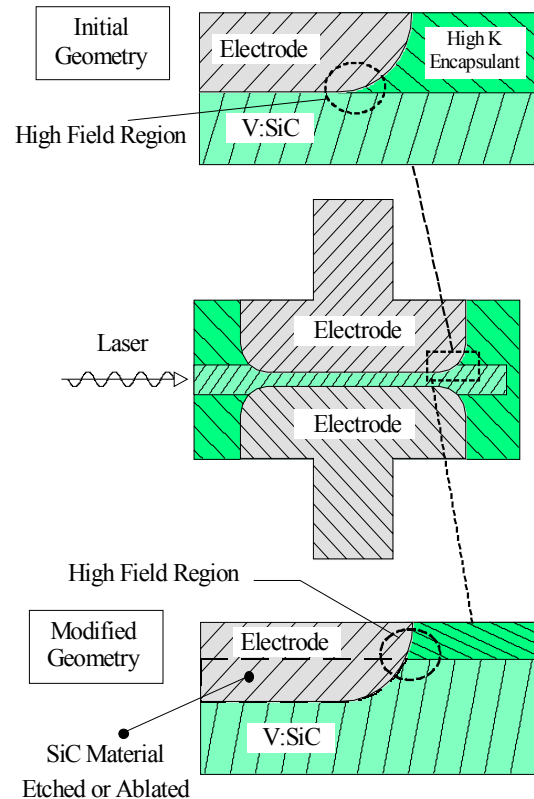


Figure 11. Electrode Geometry Modifications

package fabrication methods. The present package limitation, indicated in the top portion of Fig. 11, is the extremely large electric fields that appear in the region where the electrode leaves contact with the SiC slab. In this region, the difference in dielectric constants enhances the electric field to the point that the local electric field exceeds the bulk dielectric strength of the SiC (3 MV/cm). Switch failures have occurred at the edge of the Ohmic contacts in the high field region. The SiC switch material was fabricated such that the surfaces were

perpendicular to the SiC growth direction and thus parallel to the micropipe grown direction. Voltages up to 12 kV were applied to the approximately 0.5 cm^2 area, 400 micron thick slab of 6HV:SiC. Switch voltage failure occurred at electric fields of $\sim 300 \text{ kV/cm}$.

Two fabrication approaches are being pursued in the package development area. The first method to be evaluated is the sculpturing of the surface of the SiC to reduce the electric field at the triple point. This approach will be conducted using a combination of etching and excimer laser ablation to form the contact surface at some depth in the SiC surface as illustrated in the lower part of Fig. 9. This approach reduces the geometric electric field at the triple point and increases the viability of casting the high dielectric constant, nano particle dielectric material into the region which further reduces and shapes the electric field distribution.

4. PHYSICS MODELS AND CALIBRATION

Experimentation was used to calibrate the semiconductor physics models and to determine the density of the individual dopants and their recombination cross sections. For example, the current pulse in Fig. 12 was matched by adjusting the optical input power density, the donor and acceptor densities and the related recombination cross sections in the Silvaco™ codes. The extended conduction after the main pulse in the experimental current waveform of Fig. 12 is explained by

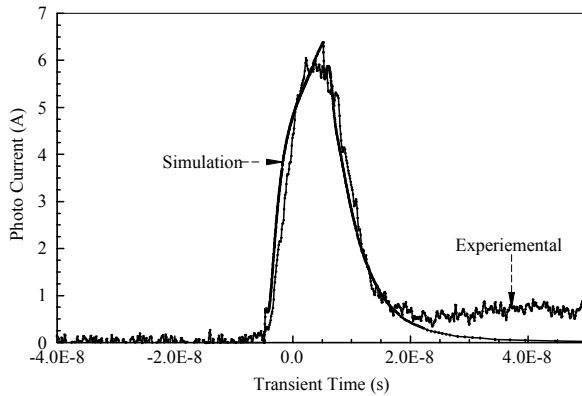


Figure 12. Experimental Model Correlation

the trapping time of the deep levels in the band gap.

The compensation ratio of the semi-insulating SiC determines the blocking resistivity of the switch, as illustrated in Fig. 13. These simulations were used to calculate the trap density of the experimental switch samples.

The trap density in the SiC material determines the blocking voltage capability of the switch, as shown in the low voltage current-voltage plots of Fig. 14. The trap density serves to capture electrons that lead to avalanche breakdown. Matching the model output with the

experimental data of these plots is used to determine the trap density and recombination cross sections.

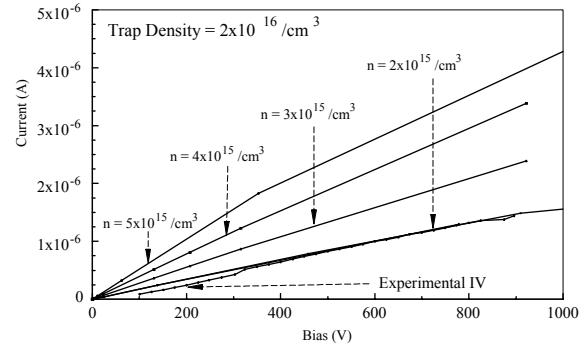


Figure 13. Effect of compensation ratio on the slope of the IV characteristics

Note that Vanadium compensated SiC has similar properties to that of semi-insulating GaAs. The materials are trap dominated, that is, the characteristics of the material are determined by the densities and recombination cross sections of the interband traps, donors, and acceptors.

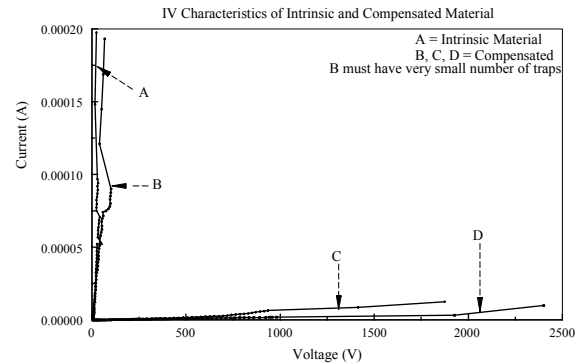


Fig 14. Experimental I-V characteristics (Low voltage) for material characterization

5. CONCLUSIONS

The capability to field a compact high voltage, pulse power supply system for directed energy systems requires the functions of voltage scaling, pulse shaping, and pulse energy storage to be contained in the same volume. The stacked Blumlein line (SBL) system is one architecture that incorporates these three functions in the same volume in a manner such that the SBL system volume can approach the absolute minimum system volume. The absolutely critical component of a high current SBL are the stage switches which must operate at high voltages, high currents and operate with precise temporal closure control, rapid resistive transition and conduct current such that the inductance of the switch is very low.

One of the few, if not the only, technologies that can provide the desired switch performance is bulk photoconductivity. Linear photoconductive switches are unique in that the location of current flow is determined by the location of optical closure energy injection, which enables the current flow to be distributed over a wide region, which results in the lowest possible switch inductance. Furthermore, the resistive transition time of photoconductive devices is completely dependent upon the time in which the optical energy is delivered to the photoconductor. The resistance of a semi-insulating photoconductive switch can easily be changed up to ten orders of magnitude in nanoseconds using very common pulsed lasers. Therefore, the inductive and resistive switching times of photo-conductive switches can provide the temporal behavior necessary for compact SBLs.

This work has investigated semi-insulating, Vanadium compensated, Silicon Carbide (V:SiC) photoconductive switches through semiconductor physics modeling and preliminary experiments. The simulations and modeling results indicate that V:SiC, when operated in the extrinsic photoconductive mode, is an ideal material for high power systems with advantages over other available materials. Specifically, operation of V:SiC in the extrinsic photoconductive mode enables control of the optical absorption depth and thus current density in the switch by controlling the density of dopants in the SiC. This work also identified two compensation structures in V:SiC, specifically Shallow Donor Deep Acceptor and Deep Donor Shallow Acceptor, and identified the behavior of these compensation structures in terms of switch photo carrier recombination times. The major advantage of V:SiC material in photoconductive switch applications is the very large dielectric strength which permits the thickness of the material to be much smaller than that required by other materials for a given blocking voltage. The small dimensions in the direction of the applied electric field results in very reasonable quantities of optical closure energies and it compensates for the low mobility of SiC for a given conduction resistance. A further advantage of SiC when compared to other materials is the very large thermal conductivity.

Another major portion of this work is the preliminary development of a high current, high voltage package that enables the switch to be used in real world systems. Additional work is needed to make the package fully operational.

SBLs and the required photoconductive switches are essential for compact pulse power systems to be used in directed energy systems such as high current, electron beam, induction accelerators required for free electron lasers, high power electric discharge lasers, and high power microwave systems.

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