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Studies of high field conduction in diamond for electron beam controlled switching

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Experimental studies on a vertical metal-diamond-silicon switch structure have been conducted for potential pulsed power applications. Both the dc current-voltage characteristics and the transient switching response have been measured for a range of voltages. With a 1 μm diamond film, the switch has been seen to withstand electric fields up to 1.8 MV/cm. Our results show a polarity dependence which can be associated with current injection at the asymmetric contacts. Polarity effects were also observed in the presence of *e*-beam excitation, and arise due to nonuniform carrier generation near the diamond-silicon interface. Our switching transients were seen to follow the shape of the *e*-beam for a negative bias at the silicon substrate. For positive voltage values exceeding about 80 V however, the switch is seen to go into a persistent-photocurrent mode. This effect is a result of free carrier trapping within diamond and is enhanced by the double injection process.

I. INTRODUCTION

Development of repetitive opening switches, capable of carrying large currents and having the potential to hold off large voltages, is critical to pulsed power technology.[1] Though both diffuse discharge[2] and bulk semiconductor based switches[3] have been successfully demonstrated, the latter has apparent advantages in terms of compactness and switching speeds. The requisite conductivity modulations are obtained through an external ionizing source which provides independent jitter-free control, electrical isolation, and fast switching capability. While lasers are often used to trigger the conductivity variations, electron beams can provide a more efficient and viable alternative under certain situations.[4,5] Their wider energy ranges and variable duty cycles, larger absorption coefficients, lower costs, and higher sustained intensities can all be used to advantage for controlling power switches made of high band gap, thin layer semiconducting materials. Such *e*-beam induced switching has already been successfully demonstrated in bulk GaAs.[5] Diamond however, promises to be a better candidate for a variety of reasons. It can hold off higher voltages, has shorter carrier lifetime and hence the potential for faster turn off. Besides, diamond exhibits superior thermal conductivity providing for better heat dissipation, has lower dark currents, and is more rugged mechanically. Fortunately, recent advances in processing technology and the successful growth of high quality artificial diamond[6,7] have made it a viable material, and therefore it becomes quite meaningful to conduct studies on diamond for possible power switching applications.

In this contribution, we report our experimental observations of the high field, steady state current-voltage (*I-V*) characteristics of a metal-diamond-semiconductor switch structure. Based on our results, we shall qualitatively analyze and discuss the relevant details of high field transport. We also investigate here, aspects of electron beam induced switching in diamond. In particular, we focus on the current-voltage behavior and the polarity effects at different biasing levels. Finally, experimental data on the temporal development of both switching currents and voltages will be presented. A persistent photocurrent effect,[8,9] also sometimes referred to as the "lock-on" behavior,[10] is seen to result. It is similar in nature to that observed previously in GaAs *e*-beam switches, but the requisite electric field values are much higher.

II. dc CHARACTERISTICS

We have performed experiments to measure the room temperature field dependent electrical characteristics, both with and without an external electron beam. The samples used in our studies mainly consisted of chemical vapor deposited (CVD) grown 1 μm polycrystalline diamond films on silicon substrates. A few additional dark current measurements were also performed however, on 10 μm diamond films. The silicon was *n* type for the 1 μm samples, and almost intrinsic for the 10 μm films. Such a variation in the film thickness adds to the flexibility and allows for the study of possible size effects on the *I-V* characteristics. Pictures obtained from scanning electron microscopes (SEMs) revealed good uniformity of the diamond film with less than 5% deviation in the thickness. Typical SEM micrographs of the surfaces for the 1 μm diamond samples are shown in Fig. 1. These pictures, obtained prior to conducting the *e*-beam switching experiments, reveal that the film edges and surfaces of both diamond samples were fairly uniform in texture. Contacts to the samples were made by sputtering tantalum onto the diamond surface, followed by platinum and gold,[11] to form a vertical metal-insulator-semiconductor (MIS) structure. Such an arrangement provides for asymmetric nonlinear conduc-

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FIG. 1. SEM micrograph of the 1 μm diamond samples used in the e-beam switching experiments. The spacing between the two horizontal lines is 1 μm. The pictures reveal good uniformity of the polycrystalline diamond film.

tion and in principle, allows for some flexibility in changing the switching characteristics through polarity reversals.

The current-voltage curves for the 1 μm diamond samples obtained in the absence of external excitation, are shown in Fig. 2 and correspond to positive and negative biasing on the silicon. As evident from the figure, the *I-V* characteristics exhibit nearly Ohmic behavior at low current magnitudes. However with positive polarity, a transition occurs roughly around 40 V and the slope increases.

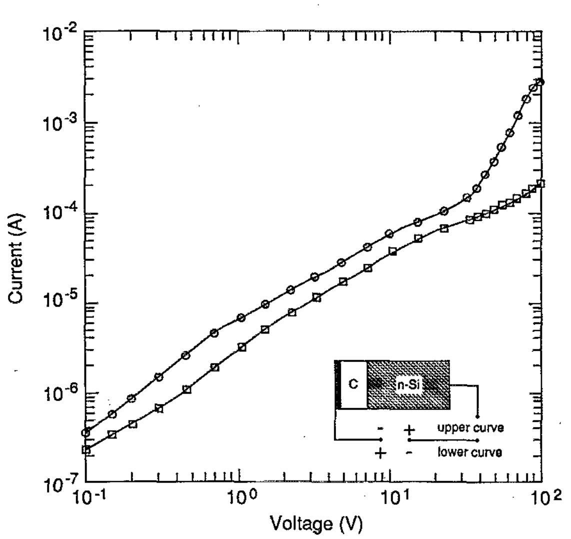

FIG. 2. The current-voltage characteristics for the 1 μm metal-diamond-silicon switch structure at 300 K. The positive and negative curves refer to the polarity of the substrate voltage.

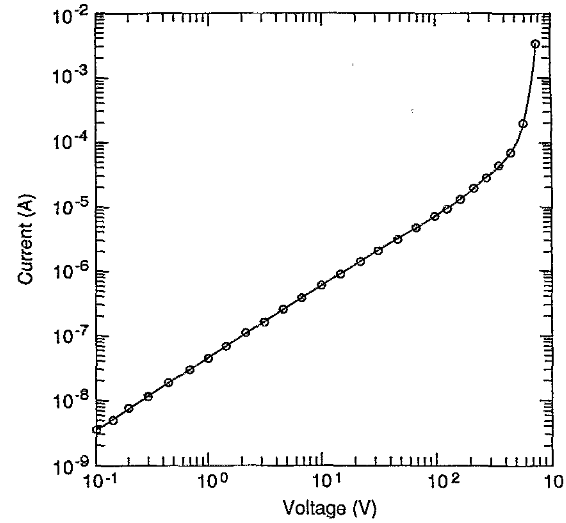

FIG. 3. Experimental current-voltage characteristics for the 10 μm metal-diamond-silicon switch structure at 300 K. The data shown corresponds to a negative polarity at the substrate.

Also obvious from the plots is that the current levels with negative biasing turn out to be correspondingly lower in value over the entire voltage range. This can be attributed to the higher electron injection capability of the metal in comparison to silicon, and to the difference in effective barrier heights between the metal-diamond and the silicon-diamond interfaces. Results of dark current measurements performed on the thicker 10 μm diamond switch structures are shown in Fig. 3. The trend in keeping with the previous data, is towards Ohmic behavior at low voltages followed by exponential type deviations beyond 150 V. As will be discussed later, the sharp increases in the current may be attributed to possible space-charge modifications and an internal Schottky effect. Though dark currents for a positive polarity are not shown here, they consistently turned out to be higher in magnitude than those obtained with a negative polarity.

In order to adequately understand the experimental data, we begin by examining the various transport mechanisms within diamond. Of these, thermionic emission would be negligible given the large barrier height and the relatively modest operating temperature. Though the exact barrier heights for the metal-diamond and the silicon-diamond interfaces are not accurately known, their values are expected to be about half of the diamond band gap. A more relevant mechanism in the present context is thermally assisted hopping[12] which imparts an Ohmic characteristic. As first suggested by Mead[13] and Sze,[14] this bulk-controlled conduction mechanism in insulating films is important at low electric fields. A consequence of such transport in this low field regime is an exponential dependence on the inverse operating temperature. Consequently for operation at the low voltage end, the current levels are expected to be enhanced with increases in the effective carrier temperature. Though we did not physically heat the device structure to test the above, the samples were sub-

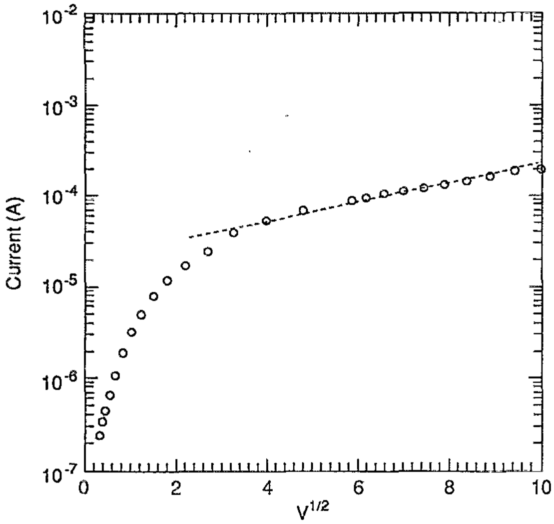

FIG. 4. Plot of Ln(I) vs $V^{1/2}$ obtained by redrawing the experimental data of Fig. 2.

jected to repetitive cycling through a large dc bias during the experimental measurements. This worked towards changing the internal temperature, and in keeping with expectations, minor current deviations did result. In absolute terms however, the current magnitudes remained very low. More significant shifts can be expected if the samples were to be cooled down to around liquid nitrogen temperatures.

At higher electric fields quantum-mechanical transitions from the trap to the continuum states begin to play an important role and deviations from Ohmic behavior result. The relevant mechanisms include Poole–Frenkel emission,[15] as well as elastic and phonon-assisted tunneling into both the conduction and valance bands. Other possible bulk mechanisms, such as the trap-to-band impact ionization, can be expected to play a negligible role at these relatively low current densities. The current-voltage characteristics at intermediate fields and beyond the initial Ohmic regime can be adequately understood in terms of the field enhanced barrier lowering effect at the contacts. As is well known, carrier injection efficiency increases with the electric field and the I-V curve roughly assumes the mathematical form: $\mathrm{Ln}(I)=K_1+K_2V^{1/2}$ with K_1 and K_2 being constants. This behavior is more clearly seen by redrawing the previous data on a semilog scale. A typical result for the 1 μm sample is shown in Fig. 4. Physically, this enhanced conduction associated with stronger carrier injection at the contacts is maintained within the bulk region through a higher drift component and supported by phonon- and field-assisted detrapping[16] to maintain current continuity. It is important to emphasize here that despite possible contributions from quantum-mechanical tunneling at the interface, the overall shape of the current-voltage curve is not expected to exhibit any significant deviation.[17] However, it must be stressed that the use of the above I-V relation is justified only as long as space-charge effects are not dominant. As will be shown subsequently, the slope can significantly change as a result of space-charge effects. Finally it may be noted that the asymmetry seen in the I-V curves via a polarity reversal, is inherent to the system for the two following reasons. First, the dielectric constants of the metal-diamond-semiconductor system are asymmetric. This effectively means that the image charges induced at the two interfaces are slightly different, and leads to dissimilar lowering of the effective barriers. Second, the zero-field barrier heights themselves are different for the two cases.

The origin of the large current increases at the higher electric fields is less clear, and we propose three possible mechanisms which could contribute to such an effect. The first involves the formation of an inversion layer within the silicon substrate, and hence is strongly polarity dependent. It however requires the existence of appropriate deep levels within diamond. The second involves space-charge effects arising from self-consistent solutions of Poisson's equation. The last involves trap filling and an increase in both the conductivity and free carrier lifetime.[18] We begin by examining the first possibility. At low positive voltages applied to the substrate, the band bending in n-silicon for the 1 μm sample is not appreciable, and consequently any hole concentration near the interface is almost negligible. This effectively precludes hole tunneling from filled traps within diamond into the silicon valance band since an empty state is not available. With increasing bias however, the silicon layer inverts, initiating tunneling from filled traps within diamond situated close to the interface. Such a process can be expected to be important given the lattice mismatch which leads to the creation of a large trap/defect density near the diamond-silicon interface. For such a scenario to be valid however, the expected inversion threshold voltage has to have a value near the experimental level of 34 V. A simple calculation for the MIS structure based on the depletion approximation for a diamond thickness $t_c=1$ μm, an n-silicon concentration N_D of 10^{17} cm^{-3}, and dielectric constants of $K_c=5.7$ and $K_{\mathrm{Si}}=11.9$ for the diamond and silicon, respectively, does indeed yield a numerical threshold value of 33.6 V in excellent agreement with the experimental data. This threshold voltage V_{th} can be obtained through the expression:

$$V_{\mathrm{th}}=2V_B+[\sqrt{4\epsilon_0K_{\mathrm{Si}}\,eN_DV_B}/(\epsilon_0K_c/t_c)], \qquad (1)$$

with $eV_B=E_{F\mathrm{Si}}-E_{i\mathrm{Si}}=E_{g\mathrm{Si}}/2-kT\mathrm{Ln}[N_{c\mathrm{Si}}/N_D]$. In the above, $E_{F\mathrm{Si}}$, $E_{i\mathrm{Si}}$, and $E_{g\mathrm{Si}}$, are respectively, the Fermi energy, the intrinsic level, and the band gap in silicon, while T is the temperature in degrees Kelvin and $N_{c\mathrm{Si}}$ the effective electron density of states. Such an inversion layer formation and hence a tunnelling current contribution, would not occur for a negatively biased substrate, thus explaining the polarity difference seen in our results for the 1 μm samples.

The above scenario requires the existence of at least one trap level within diamond between the midgap and the valance band. An upperbound for such an energy level E_T can be crudely estimated from the difference between the silicon and diamond valence band edges. This works out to be: $E_T\approx\phi_M+\Delta-E_{g\mathrm{Si}}$ relative to the diamond valance band edge, where $\Delta = kT\text{Ln}[N_{c\text{Si}}/N_D]$, ϕ_M is the difference between the metallic Fermi level and the diamond conduction band edge, and $E_{g\text{Si}}$ the silicon band gap. Assuming ϕ_M to roughly equal half the diamond band gap, E_T has an upperbound of about 1.75 eV. It must be emphasized however, that a distribution of trap levels and the occurrence of both elastic and thermally assisted inelastic tunneling prevents a more precise analysis. A quantitative investigation would require careful field and temperature dependent spectroscopic studies.

In this context it may be noted that a sudden onset of trap filling[18] accompanied by a quenching of the local potential barriers will also lead to a significant current increase. Recent numerical simulations for diamond performed on the basis of a simple drift-diffusion model incorporating five trap levels,[9] confirm the above notion. However, an exact analysis remains difficult since many of the relevant parameters such as the trap levels and their densities are not adequately known. Furthermore, defect profiles within the diamond film depend on the processing technique, and cannot be easily characterized. Finally, the physics of the observed polarity dependence in the context of spatially dependent trap filling is expected to be further complicated by nonideal and asymmetric injection at the contacts.

A third effect contributing to the strong current increase at the higher voltages is associated with space-charge limited transport. An exact analysis is again difficult since detailed information relating to the trap energies and their concentrations is not available. However, some qualitative insight into the role of the space charge can be attempted through the following crude model. Considering only one-dimensional electronic transport, Poisson's equation for the electric field $E(x)$ in the linear regime yields:

$$\frac{dE(x)}{dx} = -\frac{en(x)}{\epsilon} = -\frac{J}{\mu\epsilon E(x)}, \tag{2}$$

where μ is the carrier mobility, ϵ the permittivity, and J the constant current density throughout the sample. Besides neglecting ionized traps, the above formulation assumes a field independent mobility. Choosing $V(x=0)=0$ and $|E(x=0)|=E_c$ as the appropriate boundary conditions at the injecting cathode contact, the following expression for the overall device voltage results:

$$V = -\frac{\epsilon\mu}{3J}\left[\left(E_c^2 - \frac{2JL}{\epsilon\mu}\right)^{3/2} - E_c^3\right], \tag{3}$$

with L being the device length. For a Schottky emission process, the above current density J is related to the electric field E_c at the contact through:

$$J = -\frac{4\pi m^* e k^2 T^2}{h^3}\exp\left(-\frac{[e\phi - \sqrt{e^3 E_c/(4\pi\epsilon)}]}{kT}\right), \tag{4}$$

with k being the Boltzmann constant, ϕ the effective barrier height, m^* the effective mass, and T the operating temperature. As a result, the slope: $d[\text{Ln}(I)]/\{d[\text{Ln}(V)]\}$ turns out to be:

$$\frac{d[\ln(I)]}{d[\ln(V)]} = \frac{1}{(L/V)\sqrt{E_c^2 - (2LI/\epsilon\mu A)} - 1}, \tag{5}$$

with I being the total current and A the device cross-sectional area. When contributions from the current term are much smaller than those of the E_c^2 term, the magnitude of the slope tends towards a large value.

Consequently it follows that over a regime, wherein the current levels are sufficiently high to make space-charge effects important, and yet stay low enough in comparison with the $[\epsilon\mu A E_c^2/(2L)]$ factor, one can expect the slope to have a high value. Quite obviously, the presence of ionized trap states within diamond will change the above calculation, but the basic feature should remain. Also based on the above reasoning, one expects the I-V characteristics to exhibit the Schottky relation of Eq. (4) for biasing levels below the threshold for space-charge nonlinearities. Fortunately, such a possibility is adequately substantiated by the experimental evidence of Fig. 4 where the dc curves do reveal a Schottky characteristic. The physics behind the large current increase with modest voltage increments, can alternatively be understood in the following manner. An enhancement in the electric field at the injecting contact causes a sharp increase in the current due to Schottky emission as in (4). Hence a large supply of carriers is made available with voltage increases, which can then lead to enhanced trap filling at the various sites within diamond. This accumulation in the internal charge contributes to a lowering of the electric field through Gauss' law. The net result is that the overall device voltage increases by only a modest amount.

A final comment concerns possible modifications to the Poole–Frenkel law in the presence of overlapping Coulombic potentials[19] and its implications for diamond.[20] As is well known, a possible outcome of having a high density of defects with overlapping potentials is that the current could become exponentially dependent on the voltage. Such a mechanism has been proposed by Huang *et al.*[20] as being responsible for sharp current increases. In our case however, this effect does not appear to be important. We do not see an exponential dependence at high fields as apparent from Figs. 2–4.

III. *e*-BEAM INDUCED SWITCHING

Besides the dark current measurements, experiments were also performed to study the *e*-beam switching characteristics in the diamond structure. The overall circuit described in detail elsewhere[5] included a pulse forming network (PFN) consisting of a chain of inductors and capacitors to produce the biasing pulses. A 1:11 step-up pulse transformer was used, and the PFN terminated by a 23 Ω resistor. An *e*-beam source with a pulse duration of 15 μs produced by a pulsed thermionic diode was then directed towards the diamond film. The electron energy of the system was variable from 100 to 160 keV with an electron current density up to 35 mA/cm^2. The biasing voltage pulse had a 35 μs duration. Results of the temporal development of the switch voltage and current density obtained

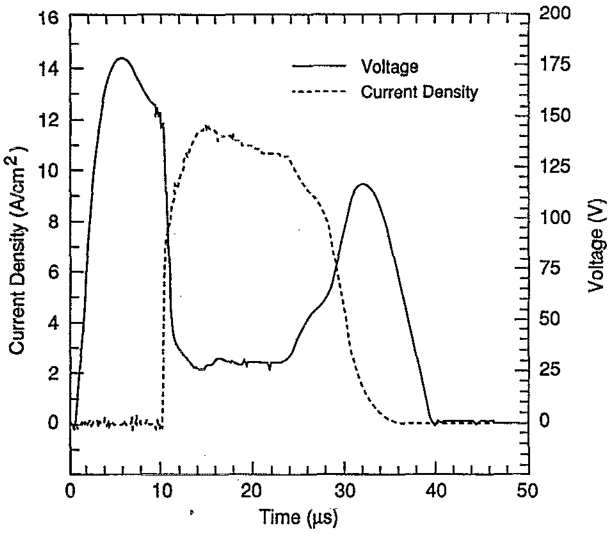

FIG. 5. Temporal development of the switch voltage and current density for the 1 μm *e*-beam activated diamond switch. The silicon substrate was negatively biased.

for the 1 μm sample with the *n*-silicon negatively biased are shown in Fig. 5. The applied voltage was varied up to a value of 180 V, corresponding to a field strength of up to 1.8 MV/cm. This high value of the electric field favorably demonstrates the capability of such a switch for pulsed power applications.

The current-voltage behavior of the 1 μm diamond switch in the presence of electron-beam activation is shown in Fig. 6. These characteristics represent a steady-state situation and roughly correspond to time instants of about 20 μs after the *e*-beam pulse initiation. As apparent from the data and the inset diagram, the relative polarity of the applied bias has a distinct effect. However in this case, the *e*-beam induced conductivity is relatively higher with the

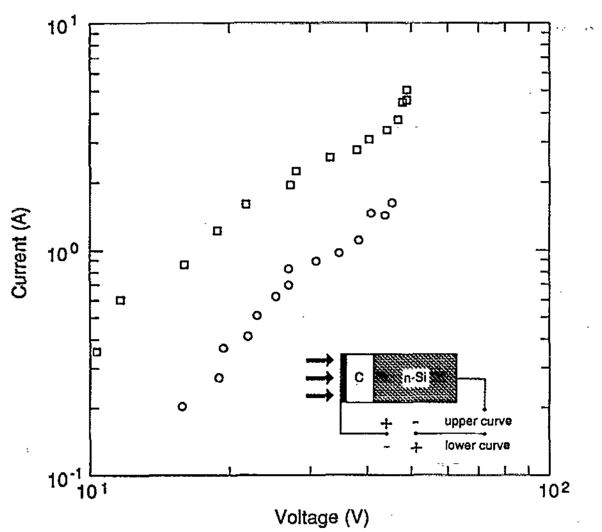

FIG. 6. Steady state current-voltage characteristics for the electron beam activated diamond switch structure. Effect of the biasing polarity is clearly seen.

substrate biased *negatively*, and thus in apparent conflict with the dark current results. In order to understand this situation, differences caused by the *e*-beam irradiation have to be carefully taken into account. Though a complete understanding and interpretation of the data requires rigorous and quantitative analysis, the important features can once again be qualitatively understood. The *e*-beam induces strong electron-hole pair generation within both the diamond and silicon sections of the sample. The relative production of excess carriers is inversely dependent on the effective band gap of the two materials, and also on the rate at which the incoming electrons lose energy through inelastic collisions. The first factor favors a much larger creation of electron-hole pairs on the silicon side of the interface as compared to the diamond side. The second energy loss term depends on a variety of parameters including the electron energy, atomic number and weight of the target material, and the material density.[21] Based on the Bethe continuous loss approximation,[22] and using the parameters for the silicon-diamond system, one can crudely obtain a ratio of the generation rates on either side. As it turns out, the silicon side of the interface has a much larger carrier generation. More rigorous Monte Carlo calculations are currently under way to quantitatively address this issue, and the results will be discussed elsewhere.

An important consequence of this discontinuity in excess carrier generation at the silicon-diamond heterojunction is that a diffusive flux component is automatically set up under *e*-beam bombardment. An occurrence of this sharp density gradient is therefore expected to provide a unidirectional driving force for carrier transport which is independent of the biasing polarity. Consequently, with a positive bias applied to the silicon, this diffusive component would work to impede and oppose electronic drift from the top metallic contact towards the silicon contact. The net current flow would therefore not be as large. On the other hand, with negative voltage applied to the silicon substrate, both the drift and diffusion components at the injecting heterointerface would be additive and lead to higher current values. Such behavior is indeed evident in our experimental curves of Fig. 6. A similar trend was also manifested in the transient switching characteristics. The peak current value in the ON state was found to be higher with the negative silicon polarity.

We finally turn to the anomalous "lock-on" effect in the *e*-beam triggered diamond switch. This lock-on mode has previously been observed in materials such as GaAs,[10,23] InP,[23] and manifests itself as a combination of persistent photoconductivity and a change in the differential resistance.[24] It is known to occur beyond some critical threshold electric field which depends on the material system. In the present case, application of bias values above 80 V for the 1 μm diamond structure with the silicon held at a positive potential caused the switch to go into lock-on. Instead of fully recovering back to its high value after the termination of the electron beam, the switch voltage exhibited only a partial increase. The temporal development of both the current density and voltage for such a situation is shown in Fig. 7. The applied biasing pulse for this case was

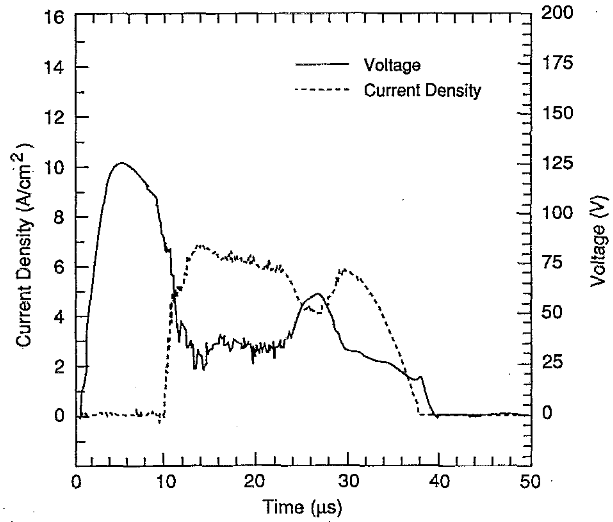

FIG. 7. Temporal development of the *e*-beam activated switch current density and voltage with the substrate biased positively. The applied voltage was about 125 V.

around 125 V with a duration of 35 μs. As evident from the curves, the voltage began to recover from about 35 V as the *e*-beam was turned off. After about 5 μs however, an avalanche-type process seemed to be initiated and the voltage began to decrease with a corresponding increase in the device current.

The lock-on behavior is not quantitatively understood with great accuracy at present, but double injection and trap related internal space-charge effects are believed to be possible mechanisms responsible for the phenomena.[5] In a general sense, the lock-on mode represents a transition into a state where the effective sample resistance is lowered from its initial value. Physically, such a transition could be caused by quenching local potential barriers to current flow that might have initially existed, through a trap filling process. Consequently, evolution into the lock-on mode requires the supply of carriers either via current injection at the contacts[18] or through an external source of electron-hole generation, to provide the requisite charge for trap filling. For the diamond switch structure being discussed here, the possible onset of hole tunneling at the diamond-silicon interface following the formation of an inversion layer might provide the mechanism for hole injection at one of the contacts. In this manner, conditions for double injection would be more easily established for the positive polarity, in keeping with the observed data of Fig. 7. Since this effect has not been strongly observed with the negative polarity, it suggests that a proper choice of contacts and biasing might provide a possible solution for curtailing lock-on. However it must be mentioned that possible hot electron effects at high voltages might eventually work to offset advantages of the negatively biased configuration. For example, impact ionization and the creation of holes via band-to-band transitions within silicon by incoming hot electrons from the diamond side, might create a pool of holes near the diamond-silicon interface. As a result, some detrimental double injection at the high voltage levels is probably inevitable despite a negative polarity arrangement.

IV. CONCLUSIONS

Experiments to determine the electrical behavior of asymmetric metal-diamond-silicon switch structures were performed. These studies were aimed at evaluating diamond as a potential candidate for pulsed power applications. Steady state current-voltage characteristics were measured at room temperature, with and without external *e*-beam excitation. Dark current measurements performed on 1 μm CVD grown diamond exhibited a strong polarity dependence. The slope of the *I-V* curve was seen to change abruptly at a field of about 0.35 MV/cm when a positive bias was applied to the substrate, but not for the opposite polarity biasing. The field field transport without the *e*-beam was linear at low voltages corresponding to a hopping conduction process. At intermediate fields the *I-V* characteristics roughly followed those of field enhanced Schottky emission. In this regime the conduction is probably controlled by the contact potentials and the electric fields in the surrounding region. At higher voltages, a strong increase in the current was observed. Though the exact physical mechanism is not clear at present, space-charge effects, field controlled detrapping, and hole tunneling are likely to contribute.

A polarity dependence was once again observed for the 1 μm diamond switch structure in the presence of *e*-beam irradiation. The current values with negative substrate biasing were larger. We attribute this effect to the nonuniform electron-hole generation profile within the diamond film. As a result, the internal electric fields are expected to be less nonuniform at the metal-diamond interface, and current injection at the contacts is expected to be asymmetric leading to the observed *I-V* curves. Our observations do underscore the possibility of proper contact selection and the controlled variation of the incident beam energy and intensity to tailor the switching characteristics. Finally, the electrical transients were seen to follow the shape of the external *e*-beam at low values of the applied voltage, and the switch turn-off was well behaved. With the negative substrate bias, the switch was seen to withstand electric fields as high as 1.8 MV/cm. For the positive polarity however, a lock-on effect developed for voltages exceeding 80 V. This is the first time that such an effect has been observed in indirect semiconducting materials. The corresponding fields were in excess of 0.8 MV/cm, and the corresponding threshold voltage can be expected to be increased by up-scaling the dimensions. It is also probable that this effect can be suppressed by an appropriate choice of contacts and the polarity of the external biasing.

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