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An Impact Ionization Model for Optically-Triggered Current Filaments in GaAs

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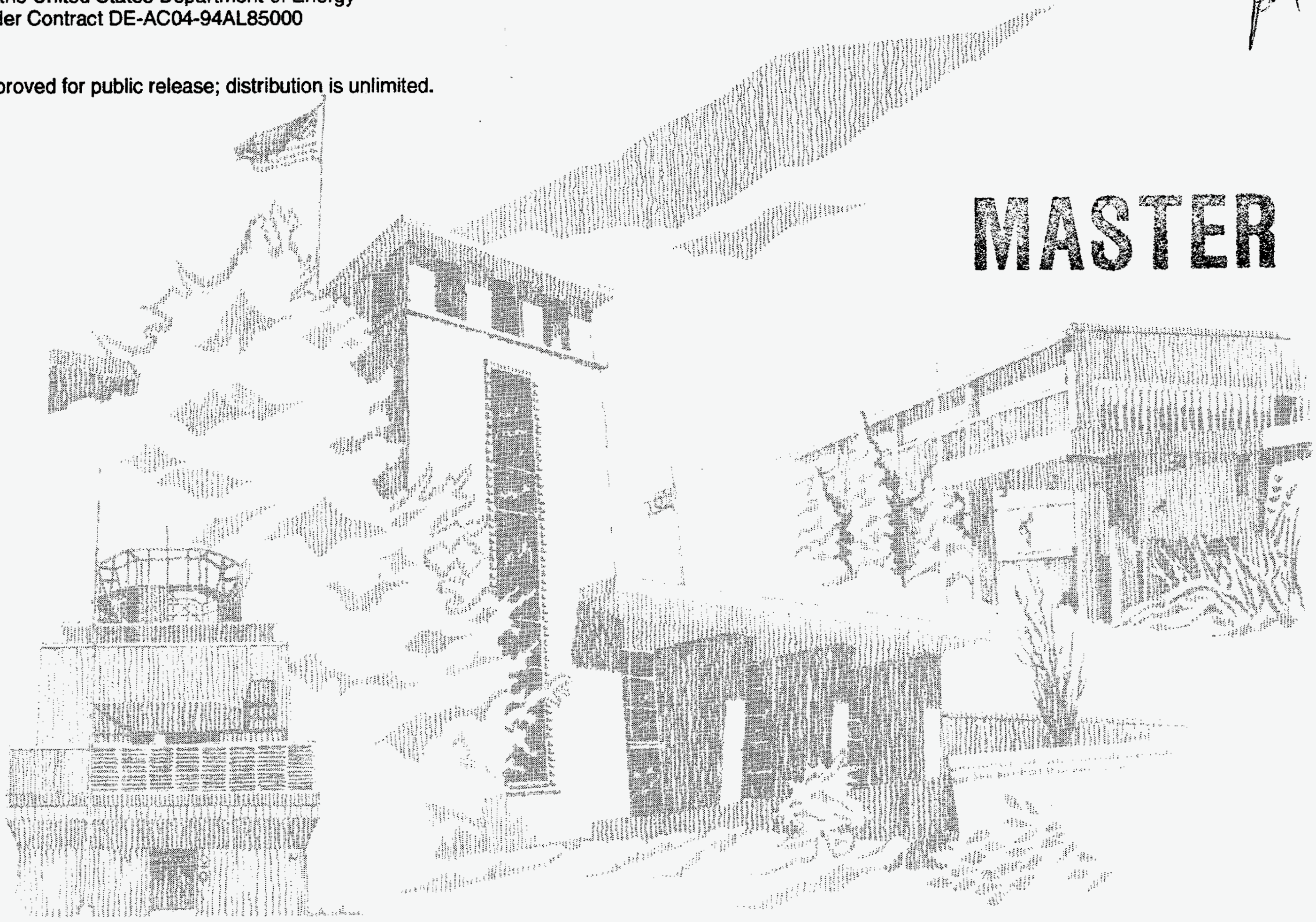

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Abstract

A new impact ionization theory is proposed for current filaments in optically triggered semi-insulating (SI) GaAs switches. The theory explains the rapid switching and lock-on voltage observed in these switches in terms of hot carriers which become more effective at impact ionization at high carrier densities. The theory is implemented by hydrodynamic transport equations which include kinetic terms for hot carriers and hot phonons. The solutions of these equations are in good agreement with current versus voltage data for optically triggered GaAs switches.

1 Introduction

The invention of the first solid-state switch, the transistor, led to replacement of vacuum tubes and numerous new applications. The development of a high-voltage, solid-state switch may lead to replacement of presently used gas discharge tubes and new applications such as control of pulsed power sources. High-voltage photoconductive switches usually operate in the linear mode in which each absorbed photon generates at most one electron-hole pair which contributes to conductivity; these carriers must be continually replenished because they recombine. In contrast, certain photoconductive switches, such as semi-insulating (SI) GaAs switches, can be optically triggered into a sustained ON state which is called lock-on (many experiments and models are discussed in Ref. 3).[1, 2, 3] This high-gain or non-linear state is technologically important because optical energy, which is expensive for high-voltage applications, is not required to maintain the ON state of the switch. For this sustained state, the switch voltage corresponds to an average lock-on field $F_{LO} \approx 4 - 8$ kV/cm.[1, 2]

The lock-on phenomenon is similar to those observed in a gas discharge tube following avalanche breakdown.[4] In this process, the energy released during a collision between a field-accelerated electron and a gas atom can ionize the atom if the impact energy exceeds the binding energy of the atom. The ionized electron can lead to an avalanche of electrons and ions. This impact ionization also occurs in solids such as GaAs if the electron impact energy exceeds the bandgap energy. Continuing this analogy, optical imaging has shown that the lock-on current is filamentary. [5, 6] In fact, these filaments appear similar to lightning, nature's example of this phenomenon. Also, time-resolved experiments on arcs have shown they propagate rapidly with a velocity which exceeds the electron drift velocity.[7] By analogy, filaments have also been shown to have large propagation velocities which exceed the drift velocity in GaAs. [8]

The most puzzling aspect of lock-on is the low electric field required to initiate and sustain it. Early experimental work found that triggering to lock-on occurred at an average threshold field $F_t \approx 20 - 30$ kV/cm.[3] This threshold field and the lock-on field are both much lower than the bulk avalanche breakdown field $F_a \approx 400$ kV/cm for GaAs.[9] These facts led to models in which the field is greatly enhanced in some manner leading to conventional impact ionization within the field-enhanced region. [10, 11, 12, 13] In the most recent models, a large field enhancement (a factor of 10-20) is used for generation and propagation of current filaments after localized optical initiation.[12, 13]

In this report, we describe a new model in which the optically-injected carriers trigger impact ionization. The impact ionization leads to stable, filamentary current flow sustained by a reduced electric field, the lock-on field. The key to our model has been to focus on how lock-on can be sustained at a reduced field rather than how lock-on can be initiated by an enhanced field. Field enhancements play no fundamental role in our model but are not excluded as they can arise from geometric effects. To test this model, we conducted an experiment, to be described, in which field enhancements are minimized. The agreement between the theory and the experiment lends strong support for our model.

In conventional impact ionization, the two primary cooling mechanisms are optical phonon emission and the impact ionization itself.[14] Optical phonon emission is the most important process at the low carrier densities prior to the onset of impact ionization. [14] At fields lower than the threshold, carriers cannot acquire enough energy to produce band-to-band impact ionization because optical phonon emission is very effective at cooling carriers whose energy exceeds the optical phonon energy. The resultant non-thermal distribution function has an average energy which is large compared with optical phonon energies but which has no high energy exponential "tail" characteristic of a thermal distribution. To a good approximation, conventional impact ionization occurs at fields large enough that a carrier acquires approximately a bandgap of kinetic energy prior to phonon scattering. However, this phenomenon is much different at the higher carrier densities important to initiation of lock-on.

The key mechanism in our lock-on model is more effective carrier heating (per carrier) at high carrier densities. This occurs in two principal ways. First, the optical-phonon cooling rate is reduced. The high carrier densities overwhelm the cooling effectiveness of the smaller density of zone-center LO phonons; screening also reduces the rate of both LO and transverse-optical (TO)-phonon emission. [15] Thus carrier cooling per carrier becomes ineffective at high carrier densities and fields comparable with the lock-on threshold field. Second, carrier-carrier scattering, such as intra-band Auger transitions, redistributes the heat from the field producing a thermal carrier distribution. In contrast with the phenomena at low carrier densities, this distribution has a "tail" which can produce impact ionization. Both these effects contribute to produce impact ionization at reduced threshold fields compared with those of conventional impact ionization.

2 Experiment

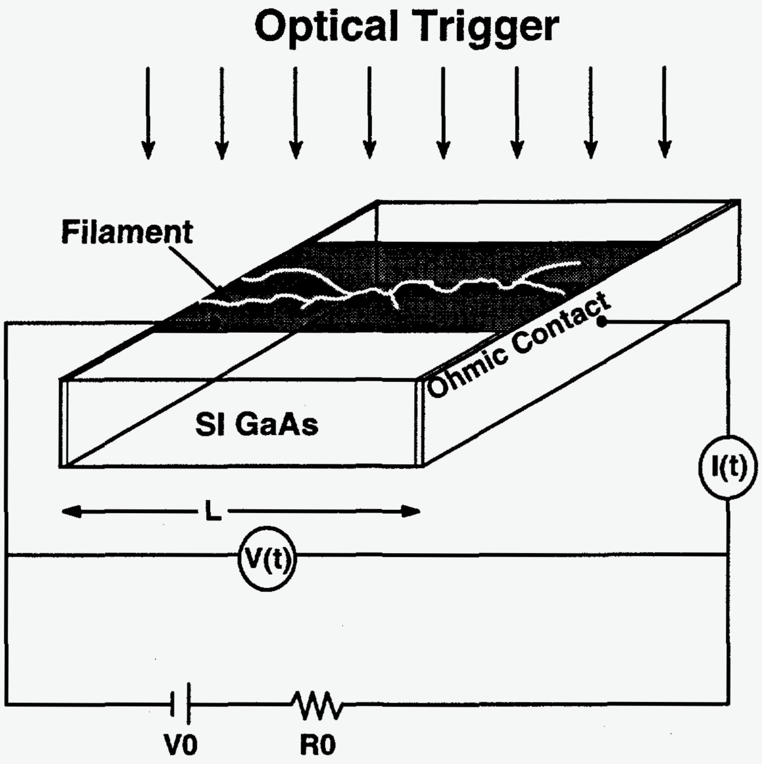

Figure 1: Schematic of an optically-triggered switch. The stripe-focus illumination is uniform along the direction of current flow to minimize electric field enhancements.

To test the importance of this mechanism while minimizing the effects of electric field enhancement, we performed the experiment shown in Fig. 1. The current flows in the y-direction between contacts separated by a distance $L \approx 1$ cm; the optical triggering beam is directed into the switch in the z-direction with a width σ_x in the x-direction (see Fig. 1). This stripe-focus beam is uniform between the contacts to reduce or eliminate large electric field variations or enhancements. This experiment shows that triggering with uniform stripe-focus illumination creates filaments whose luminescence appears uniform along the direction of current flow. There is no evidence for a field enhancement near a contact leading to filament growth near the enhancement.

3 Theory

We consider only this stripe-focus geometry in our calculation. The uniform, stripe-focus optical injection of the sample allows us to ignore many of the details such as contact boundary conditions. The problem is two-dimensional in space; the variables are functions of depth into the surface z, lateral position x, and time t. In this approximation the electric field $F = -V/L$ in which V is the applied voltage and L is the sample length.

The model is formulated in terms of hydrodynamic-kinetic transport equations for electrons and holes optically injected into a SI GaAs switch biased by an external circuit.[16, 9, 17] The equations consist of continuity equations

$$\begin{aligned} \partial n/\partial t &= g + B(n_i p_i - np) + A(n_i p_i - np)(n+p) + 1/q\nabla J_n \\ \partial p/\partial t &= g + B(n_i p_i - np) + A(n_i p_i - np)(n+p) - 1/q\nabla J_p \end{aligned} \tag{1}$$

for electron n, hole p, and intrinsic n_i densities, electron J_n and hole J_p currents, and optical carrier generation terms g. The impact ionization term (third term) in these equations largely controls the carrier density; the $n_i p_i$ impact ionization portion generates carriers and the np Auger portion recombines carriers. The carrier density is determined by the carrier temperature which controls the intrinsic densities. The kinetic terms depend on the radiative recombination coefficient $B = 1 \times 10^{-10}$ cm^3 sec^{-1} and the impact ionization coefficient $A = 10^{-31}$ cm^6 sec^{-1} for GaAs. [18, 19] The essence of the model is contained in energy balance equations

$$\partial(n+p)k_B T_c/\partial t = (J_n+J_p)F-(n+p)k_B(T_c-T_{LO})/\tau_{LO}-(n+p)k_B(T_c-T_L)/\tau_{TO}, \tag{2}$$

$$p_0 k_B \partial T_{LO}/\partial t = (n+p)k_B(T_c - T_{LO})/\tau_{LO} - p_0 k_B(T_{LO} - T_L)/\tau_0, \tag{3}$$

and

$$c\rho \partial T_L/\partial t = p_0 k_B (T_{LO} - T_L)/\tau_0 + (n+p) k_B (T_c - T_L)/\tau_{TO} + K\nabla^2 T_L \quad (4)$$

for the carrier T_c, LO phonon T_{LO} and lattice T_L temperatures. Equation (2) describes carrier temperature governed by electric field heating and phonon cooling. Equation (3) describes the LO-phonon temperature controlled by heating and cooling terms with the parameter p_0 defining the effective density of LO-phonon modes. Finally, Eq. (4) describes the lattice temperature through a heat equation with LO- and TO-phonon heating terms and a diffusion cooling term.

The energy balance equations and the form of the impact ionization rate in Eq. (1) are key to our model. A conventional impact ionization mechanism cannot be described by this model because the concept of carrier temperature is not valid. However, our model assumes that carrier-carrier scattering randomizes the carrier distribution function so that a carrier temperature T_c can be defined and used in the impact ionization term.

The physical parameters governing transport are well-known values for GaAs. [20] The thermal parameters are $K = 0.435$ W cm^{-1} K^{-1} and $\kappa \equiv \frac{K}{\rho c} = 025$ cm$^2 s^{-2}$.[21]The phonon relaxation times are $\tau_{LO} = 0.5 \times 10^{-13}$s, $\tau_{TO} = 1.0 \times 10^{-11}$s, and $\tau_0 = 1.0 \times 10^{-11}$s.[15, 22] Only the zone-center optical phonons are effective at carrier cooling; the effective phonon density $p_0 = 1.0 \times 10^{18}$ cm^{-3}. [23]

4 Calculations and Comparison with Data

The theory is illustrated by a particular calculation in which $V_0 = 8400$ V; the load resistance $R_0 = 74\ \Omega$ corresponds to the circuit used for the experimental data to be discussed. Fig. 2 shows the switch voltage V(t) as a function of time following a laser pulse of duration $t_p = 10^{-12}$ s. During the pulse the voltage gradually drops as carriers are injected; following the pulse the carrier density remains nearly constant for approximately 10 ps. However, the carrier and LO-phonon temperatures in the center of the illuminated volume are increasing during this time as can be seen in Fig. 2. During this time the lattice temperature remains constant. At $t \approx 10$ ps, the carrier temperature has risen enough to produce band-to-band impact ionization which creates a growing filament. The subsequent rise in carrier density cools the carriers leading to a quasi-equilibrium state in a stable filament whose carrier density is approximately 10^{20} cm^{-3} in the center.

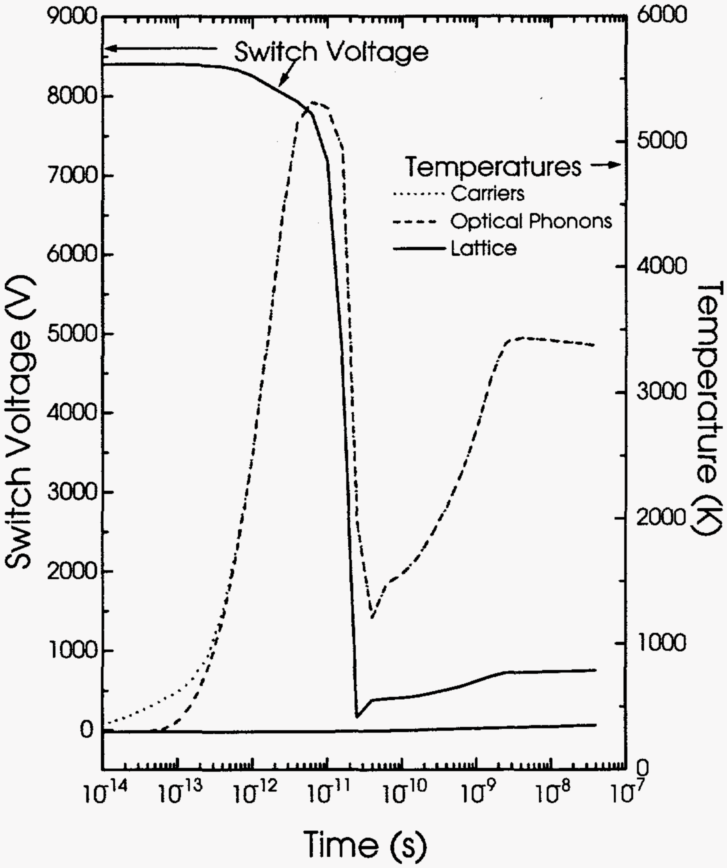

Figure 2: Switch voltage as a function of time after triggering (left axis); carrier temperature, longitudinal-optical phonon, and lattice temperature (right axis).

The LO-phonon contribution to this phenomenon can be readily understood by approximating the LO-phonon temperature as stationary in time. Then the LO-phonon carrier cooling term becomes

$$\frac{c_0}{n+p+c_0}(n+p)k_B(T_c - T_L)/\tau_{LO} \tag{5}$$

in which

$$c_0 = \frac{p_0 \tau_{LO}}{\tau_0} \tag{6}$$

By inspection, the LO-phonon cooling rate is attenuated if $(n+p) \gg c_0 \approx 10^{16}\mathrm{cm}^{-3}$; for lower injected carrier densities the LO-phonons remain effective at cooling. Due to the reduced cooling, the diffusion term in Eq. (4) is effective at maintaining the lattice temperature $T_L \approx 300$ K even at 100 ns as shown in Fig. 2.

The rapid rise in carrier density drops the switch voltage dramatically to the lock-on voltage $V_{LO} \approx 750$ V as can be seen in Fig. 2. This drop is caused by the additional loading of the power supply due to the increased current following impact ionization.

The nearly constant switch voltage beyond the switching time demonstrates that this model can successfully reproduce the experimentally observed constant lock-on field. For this particular case, the lock-on field $F_{LO} = V_{LO}/L \approx 3$ kV/cm which is a factor of two less than the empirical lock-on field of approximately 6 kV/cm. [3]

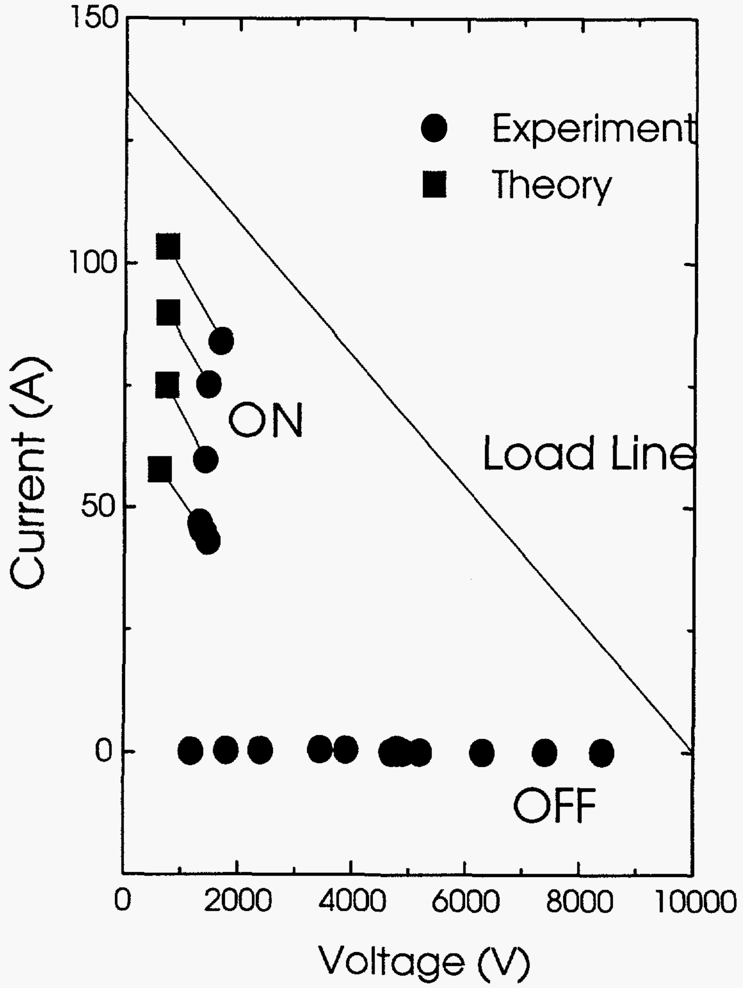

Figure 3: Theoretical current versus voltage during the ON state compared with data for an optically triggered switch.

The theory's predictions are compared with current versus voltage data in Fig. 3. The data were obtained with a transmission line circuit equivalent to that shown in Fig. 1. For each supply voltage V_0, the low OFF state current values shown in Fig. 3 were measured prior to optical triggering. The successful trigger events produced the ON state data also shown in Fig. 3. Pairs of ON and OFF states can be linked by load lines defined by the external circuit; one particular load line is shown. To compare with the data, calculations were made in which only the voltage V_0 was varied; the other parameters were the same as in Fig. 1. The current and voltage were taken from the model at a time $t = 30$ ns in agreement with the experimental conditions. By inspection of Fig. 3, one can see that the theory agrees fairly well with the data.

5 Discussion

The key feature of our theory is a mechanism for rapid initiation of lock-on which is then sustained by a modest field. The process is fast because only carriers, not the lattice, become hot. Although our present model is rudimentary in treating hot carriers and hot phonons, it captures the essence of the most important effects. Our energy balance equations can be justified but at present they are not rigorously derived (nor do they seem to appear in the literature). In particular, more work is needed to justify the use of carrier temperature prior to lock-on. Screening of LO and TO phonons, ignored in the present model, may play an important role in lock-on. An important quantitative weakness is that the parameter p_0 is not well defined. In general, the temperature-dependence of other parameters, such as the phonon lifetimes and thermal parameters, is also ignored. These weaknesses can be rectified in a more refined model.[17]

Filaments are a natural consequence because this model has two stable states, ON and OFF, for any bias voltage (see Fig. 3) leading to coexistence of high current (filaments) and low current regions in a sample. In fact, a thermal ionization model which also exhibits lock-on switching and filaments can be thought of as a long-time limit of this model.[24] We also find that, for increased switch voltage, the switching is more rapid and the laser trigger energy is reduced; these phenomena are in agreement with experiments. [17]

We conjecture that these filaments are a stable stage of conventional impact ionization. Our model exhibits dark avalanche breakdown for $F_a \approx 400$ kV/cm in agreement with conventional avalanche breakdown; [9] below F_a the model predicts that breakdown in the dark does not occur. However, both these predictions are fortunate artifacts of our model which is not valid at low carrier densities and high electric fields. We infer that conventional impact ionization leads to a filament which can fill the entire sample. This filament is sustained by a field F_{LO} which is much lower than the field F_a required to initiate impact ionization without optical triggering. Of course, at long times, the thermal stress due to heating of all the phonon modes leads to destruction of the sample.

6 Conclusion

We have described a theory which captures some of the most important features of optically triggered SI GaAs switches: (1) a lock-on field which is independent of power supply voltage and time following switching, (2) filamentary current flow, and (3) bistable switching. The quantitative results are in reasonable agreement with the experimental data. In later work we will apply this model to the propagation of a filament; our model predicts that the filaments propagate as shock waves whose carrier velocities exceed the carrier saturated drift velocity.[8, 17] Finally, we envision that this model can be applied to understanding destructive breakdown of power field-effect transistors (FETs) and single-event upset (SEU) of Si memory chips due to alpha-particle strikes. Both of these phenomena involve filamentary current flow of hot carriers at high densities.

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