Modeling of high power semiconductor switches operated in the nonlinear mode

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Although optically activated high power photoconductive semiconductor switches (PCSS) are usually triggered using uniform illumination, under select conditions they can be activated and closed in <1 ns with a spot of light near the contacts. This observation requires free carriers to either travel at speeds faster than their saturation velocity or for there to be a carrier generation mechanism that propagates with similar speeds. A two-dimensional time-dependent computer model of a GaAs high power switch has been employed to investigate these observations, and activation of PCSS by spots of light in particular. Results from the model suggest that the transport of band-to-band recombination radiation plays an important role in propagating electrons across the switch when the switch is closed with a spatially nonuniform laser pulse. Reabsorption of the recombination radiation and photogeneration of carriers is a mechanism which generates free carriers in the gap between the contacts at speeds greater than saturation velocity. The results also indicate that the switch is sensitive to the location of the activating laser pulse. Less laser fluence is required to close the switch if illumination occurs near the cathode rather than near the anode. © *1996 American Institute of Physics.* [S0021-8979(96)03004-1]

I. INTRODUCTION

High power (many to tens kV, tens A to kAs) photoconductive semiconductor switches (PCSS) operate by varying the conductivity of the semiconductor through photon absorption. Shining band-gap (or shorter wavelength) radiation from a laser on the sample generates electron–hole pairs via photon absorption thereby increasing the conductivity of the sample and closing the switch.[1–4] PCSS typically operate in linear or nonlinear switching modes. In the linear mode, there is no carrier avalanche, and so the carrier density is determined by the photon absorption. In the nonlinear mode, which is experimentally observed only in direct band-gap semiconductors, the carrier density increases not only through the absorption of the laser light but also by gain mechanisms. Although gain mechanisms such as carrier avalanche are possible in Si, the nonlinear mode has yet to be observed. The switch remains closed for the duration of laser illumination or until the photogenerated carriers recombine. Since in the linear mode the only source of excess carriers comes from the optical radiation, the change in the conductivity of the switch is nearly linearly proportional to the intensity of the optical radiation. The absence of nonlinear effects therefore allows for a more controllable closing and opening of the switch.

In the nonlinear mode, gain mechanisms associated with high electric fields (that is, above a threshold voltage) multiply the initial electron–hole pairs generated by the absorbed photons. The carriers necessary for closing the switch are therefore only partially provided by the laser photogeneration and therefore less laser fluence is required to close the switch. Possible sources of gain in the nonlinear switching mode include band-to-band impact ionization and trap impact ionization. In general the minimum optical energy required to close a switch in the nonlinear mode decreases as the average electric field across the switch increases. The functional dependence between the optical trigger energy and the applied electric field, however, is not well understood.[1]

Gain mechanisms enable closing of PCSS operating in the nonlinear mode even when the device is only partially illuminated by the trigger laser. One example of this behavior is the triggering of PCSS with a spot of light located between the contacts. When the switch is closed in this fashion, triggering is most efficient when the spot of light is physically located near the contacts. For example it is possible to close a GaAs PCSS with spots of laser light of 0.5 μJ near the cathode or 2–3 μJ near the anode. More laser energy is required to close the switch if the laser spot is centered between the contacts and the spot diameter is small compared to the contact separation.[2] Triggering the switch with small spots of light located near a contact does not appreciably change the current delay and rise times from those usually observed in PCSS operating in the nonlinear mode. This observation implies that there is a mechanism for rapid generation of carriers across the insulating gap. The method of this carrier transport is such that carriers appear to travel at speeds greater than the saturation velocity. Estimates of this speed range as high as ten times the saturation velocity.[3]

Closing PCSS in the nonlinear mode enables a large reduction in the optical trigger energy compared to the energies required when operating in the linear mode.[4] The gain that produces this reduction in the trigger energy also affects the trigger delay time (the time between application of the trigger laser and switch closure), jitter, and the rate at which the

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switch closes. These attributes are no longer directly controlled by the optical trigger as in the linear mode but also by the generation of carriers through gain mechanisms. Since all the carriers which are required for switch closure are not generated by the trigger laser, there is a delay time associated with generating the extra carriers (the trigger delay time) through gain mechanisms. The trigger delay time is generally inversely proportional to the average applied electric field across the switch. At sufficiently high voltages, the trigger delay time is short, and so the switching speed is essentially the same as a linear switch having the same carrier density. At low voltages, the trigger delay time may vary from pulse to pulse. Therefore, the jitter (a measure of the scatter in the time required for switch closure) is usually larger than that found in linear switches. The jitter, however, decreases as the voltage is increased.

The closing phase of the switching cycle is typically initiated by laser light having a photon energy greater than the GaAs band-gap energy. The absorption length of a photon having the band-gap energy in GaAs is 2 μm.[5] Therefore, carriers are generated only at the surface of the switch. If the GaAs is semi-insulating with impurity levels in the gap, a laser having subband-gap energy could be used to trigger the switch. The absorption length at these wavelengths may be long enough to generate carriers throughout the bulk of the switch. For example, 1.054 μm (Nd:glass laser) has an absorption length >1 mm[5] and carriers can be generated throughout a switch. A 10 mJ, 540 ns pulse at 1.05 μm is sufficient to lower the resistance of a 5 mm cube GaAs switch to $\approx 1\ \Omega$.[6]

The phenomenon of linear and nonlinear modes is also observed in thyristors. Current rise times in GaAs thyristors operating in a nonlinear mode are five times smaller than in Si thyristors operating in the linear mode.[7] The closing times of GaAs thyristors are also shorter than the transit time of carriers crossing the base layers when traveling at their saturation velocity.[8] It is believed that internal generation and absorption of photons within the base region are important mechanisms for the fast turn-on.[9]

Nonlinear processes in PCSS have previously been investigated by modeling and simulation.[10,11] These models have recognized different mechanisms as being important in explaining lock-on and filament formation. These mechanisms include avalanche,[12] electric field dependent trap filling,[13] metastable impact ionization,[14] localized impact ionization,[15] and double-injection and carrier trapping.[16] In this work, a previously developed model[17] to investigate GaAs(Si:Cu) PCSS has been applied to investigating the closing of PCSS by spots of light. The model is a two-dimensional drift–diffusion formulation that accounts for negative differential resistance and severe density gradients which enhance electric fields to values high enough for impact ionization to become viable. Using this model we show that photogeneration by absorption of recombination radiation is an important mechanism for generating carriers in PCSS and producing effective carrier velocities which appear to be larger than the saturation velocity. The model will be briefly described in Sec. II, followed by a discussion of our results in Sec. III. Our concluding remarks are in Sec. IV.

II. DESCRIPTION OF THE MODEL

A. Particle transport

The particle transport portion of the model we have used in this study has been previously described (Ref. 17) and so will be only briefly discussed here. The model is a two-dimensional simulation of a PCSS using a drift diffusion formalism. The previously described model addressed a bistable GaAs PCSS doped with Cu and Si. Here, we consider only intrinsic GaAs and so exclude the Cu and Si states. The densities of electrons and holes are tracked while solving Poisson's equation for the electric potential using a semi-implicit algorithm. The spatial derivatives are couched using finite difference and donor-cell techniques on a nonuniformly spaced rectilinear mesh. The 64×64 computational mesh is concentrated at the contacts. Any boundary which is not set to a voltage has the component of the electric field normal to its surface set to zero. In the circuit portion of our model the switch is in parallel with a 50 pF capacitance, and in series with a 20 nH inductor and 50 Ω load.

The semiconductor device we have modeled is an intrinsic GaAs coplanar switch. GaAs typically has residual amounts of shallow acceptors such as carbon and zinc which are trapped by the native donor EL2 thereby decreasing the free carrier concentration of the semiconductor. The absence of free carriers in the material raises its resistance to the point that it is referred to as semi-insulating GaAs. Our model does not explicitly take into account these deep trap levels and the term intrinsic GaAs is employed to emphasize the absence of these deep levels.

B. Band-to-band recombination radiation

After the production of large carrier densities from the laser pulse ($\approx 10^{17}$ cm^{-3}), recombination immediately begins. In direct band-gap semiconductors, band-to-band recombination usually produces a photon having the band-gap energy. This photon can be reabsorbed, thereby creating an electron–hole pair. With the large carrier densities typical of high power semiconductor switch operation, this reabsorption may be a significant process. For example, with carrier densities of 10^{17} cm^{-3} and a recombination coefficient of 10^{-10} cm^3 s^{-1}, the source of recombination radiation is 10^{24} cm^{-3} s^{-1} or 10^{15} cm^{-3} ns^{-1}.

Implementing transport of band-to-band recombination radiation using a full radiation transport algorithm would have unacceptably increased computer time for the calculation. As an approximation, radiation transport is implemented in the model using a diffusion formalism. It should be noted that Holstein[18] has shown that simulating the absorption and emission of light quanta cannot be formulated exactly in terms of a diffusion equation. The purpose of this work, however, is to investigate the possible importance of the effect and so the approximations we make are adequate. Holstein, however, also recognized that although using a diffusion equation for radiation transport is not exact, the treatment does show fair agreement with a full radiation transport calculation in many cases. A more thorough investigation

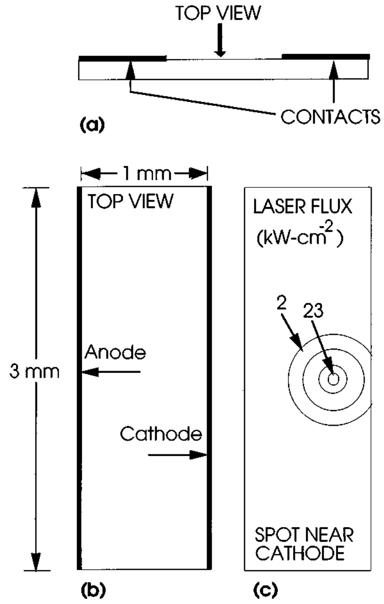

FIG. 1. Schematic of the switch geometry addressed in this study. (a) The coplanar configuration has both contacts in the same plane as shown in this side view. (b) Top view of the coplanar switch as addressed by the model. The typical dimensions are 3×1×0.4–0.5 mm^3. (c) The photon flux Φ (W cm^{-2}) distribution used in the model. It is spatially Gaussian with its peak 0.25 mm from the contact for light spot activation near the cathode.

(which these results indicate is warranted), will require a more detailed radiation transport calculation.

The recombination radiation is represented as a photon density n_ϕ, which diffuses throughout the switch to a steady-state distribution every time step ($\approx 5.0\times 10^{-13}$ s), which is commensurate with the photon transport time across the contacts. The photon transport diffusion equation used in the model is

$$\frac{d}{dt}[n_\phi]=D_\phi\nabla^2 n_\phi+n_e n_p k_r-\frac{n_\phi}{\tau_\phi}=0, \tag{1}$$

where D_ϕ is the photon diffusion coefficient, n_p and n_e are the densities of electrons and holes, k_r is the recombination coefficient, and τ_ϕ is the reabsorption time. The absorption term n_ϕ/τ_ϕ is also added to the continuity equations for electrons and holes as source terms. The values for D_ϕ and τ_ϕ are determined by equating the absorption length of the light to the absorption coefficient $\alpha = 5\times 10^3$ cm^{-1},

$$\tau_\phi \approx \left[\alpha \frac{c}{\sqrt{\epsilon_r}}\right]^{-1} \approx 10^{-14} \text{ s}, \tag{2}$$

$$D_\phi = \frac{1}{\alpha^2 \tau_\phi} \approx 4\times 10^6 \text{ cm}^2\text{/s}. \tag{3}$$

III. LIGHT ACTIVATION OF A PCSS WITH LASER SPOT

To investigate switching of PCSS in the nonlinear mode using a spot of light, we have modeled a coplanar geometry for an intrinsic GaAs switch as shown in Fig. 1(a).[1–4] The view we have addressed is from the top, as shown in Fig. 1(b). The contacts are separated by 1.0 mm and are 3.0 mm wide. The depth of the switch is 0.4–0.5 mm. The computational mesh ends at the interface between the contact and semiconductor. As a result the carriers under the contacts are not resolved. The anode (at the left-hand side) and the cathode (at the right-hand side) are both current injecting. The holdoff voltage is 3 kV. At $t=0$, only thermally generated free carriers are present. The closing laser pulse has a photon energy corresponding to the GaAs band gap, with a typical intensity distribution in the spot of $\Phi = 2$–23 kW/cm^2 as shown in Fig. 1(c). The laser pulse has a Gaussian temporal shape with a full width at half-maximum of 2 ns with the peak arriving at 6 ns. It should be emphasized that optical carrier generation is being obtained by valence-to-conduction band transitions and not through intermediate trapping levels in the gap as in some semi-insulating GaAs switches. The spatially Gaussian laser pulses spots are applied either near the anode or cathode.

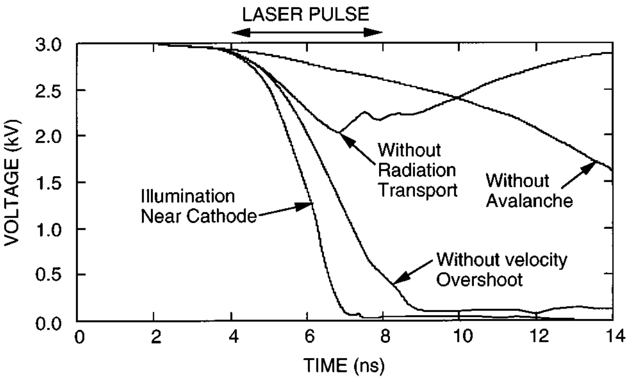

FIG. 2. Switch voltage as a function of time for a coplanar intrinsic GaAs device activated with a spot of light near the cathode ($\Phi = 10^{23}$ cm^{-2} s^{-1}). Results are also shown for excluding radiation transport, avalanche, and negative differential resistance. Radiation transport is an important process for switch closure when activating with a spot of light. Without radiation transport the switch fails to close. Without the gain mechanism provided by avalanche the switch closes at a slower rate. Without negative differential resistance the switch closes at a moderately slower rate.

Uniform illumination of the top of the switch uniformly increases the carrier concentration between the contacts, which results in a rapid reduction in the resistance of the switch. A spot of light as a trigger, however, generates carriers only locally. Some form of carrier transport is therefore required before the switch can close. That transport could simply be the drift of carriers, however the short closing times imply carrier speeds in excess of their saturation velocities. Therefore, a mechanism is required which enables carriers to traverse the switch at speeds greater than the saturation velocity in order to close the switch in the observed times. As discussed in Sec. I, one such process is transport and reabsorption of band-to-band recombination radiation.

The voltage across our switch is shown in Fig. 2 for laser spot activation near the cathode when radiation transport is and is not included. Without radiation transport, the holdoff voltage across the device was lowered only by ≈30%. The switch fails to fully close and soon recovers to its open state. With radiation transport included, the switch closes with a

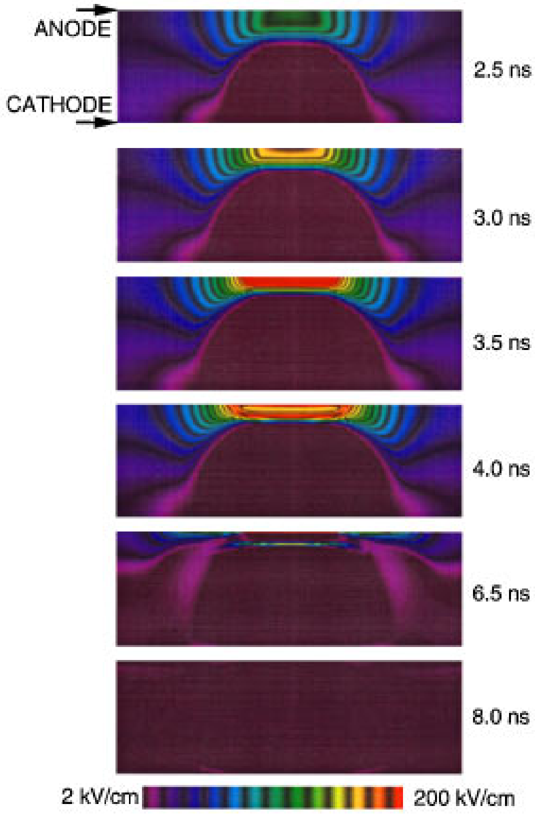

FIG. 3. Time evolution of the electric field for light activation near the cathode with radiation transport considered. The anode is at the top of each frame; the cathode is at the bottom. The electric potential is compressed near the anode when the laser spot is introduced and a conductive region is produced. At switch closure the electric field completely collapses at both anode and cathode.

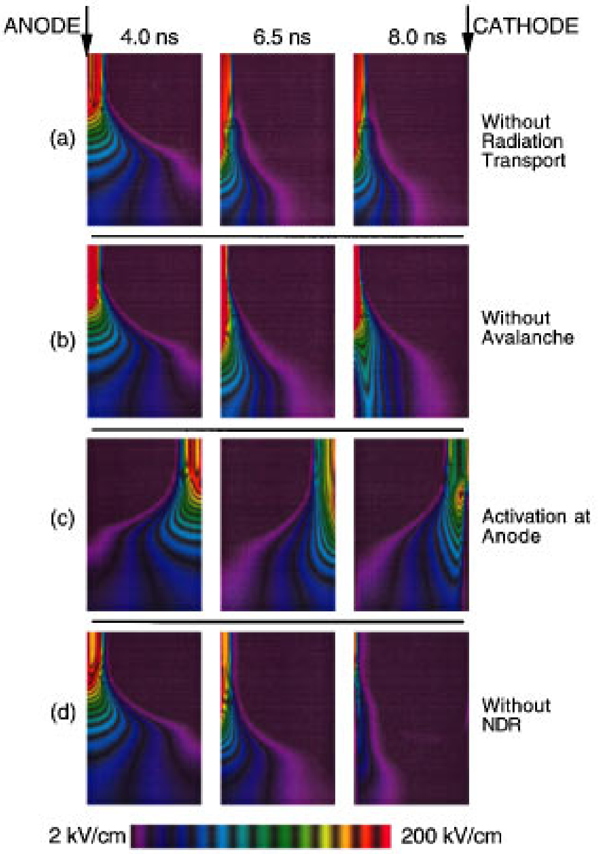

FIG. 4. Time evolution of the electric field for various conditions. The anode is at the left-head side, and cathode at the right-hand side of each frame. Values are shown only for half of the symmetric switch. Time frames are shown from left to right. Results are shown for activation (a) near the cathode without radiation transport, (b) near the cathode without carrier avalanching, (c) near the anode, and (d) near the cathode without negative differential resistance.

95% reduction in holdoff voltage 1 ns after the application of the laser pulse. For these conditions the rapid generation of small carrier densities at the leading edge of the high conductivity region by photoabsorption, coupled with avalanche, is sufficient to propagate carriers across the switch. The delay between the peak of the laser pulse (6 ns) and actual closing of the switch (7 ns) is expected given the finite trigger delay time required to produce the critical density of carriers.

It is interesting to compare the consequences of excluding or including other physical processes to determine if radiation transport is indeed a necessary process. (See Fig. 2.) If negative differential resistance and velocity overshoot are excluded while including radiation transport, the closing of the switch takes slightly longer but the switch does close. If radiation transport is included and avalanche is neglected, the device will also close but on yet a longer time scale. Avalanche appears essential for fast current rise times when spot illumination is used.

A time sequence of the spatially dependent electric field when radiation transport is included is shown in Fig. 3. The anode is at the top of each frame and the cathode is at the bottom. When the spot of light is applied near the cathode with a laser flux similar to Fig. 1(c), excess carriers are introduced which increases the conductivity in that region and excludes the electric field. The electric potential therefore compresses near the anode (2.5 ns). As switching proceeds (4 ns) the electric field continues to collapse in the higher conductivity region and the remaining voltage is compressed near the anode. As radiation transport, photogeneration, and avalanche extend the conductive region, the electric field continues to collapse and a smaller voltage is compressed at the anode. The electric field finally completely collapses at 6.5 ns, with a commensurate decrease in the switch resistance, which signals switch closure. As the potential is compressed to the anode during commutation, the rate of closure increases as the rate of avalanche increases at the front.

The absorption and reemission of band-gap radiation also lengthens the effective lifetime of the carriers in a process analogous to radiation trapping in gases.[18] As a result, radiation transport contributes to switch closure not only due to the rapid expansion of the conduction region but secondarily due to a lengthening in the effective lifetime of the carriers. No doubt the measurement of carrier lifetimes in bulk semiconductors already has a component of radiation trapping. This effect is amplified in regions of density gradients. For example, contrast the electric field which results when radiation transport is excluded, as shown in Fig. 4(a), with the electric field with radiation transport (Fig. 3). (Note that Figs. 4–6 show quantities for only half of the symmetri-

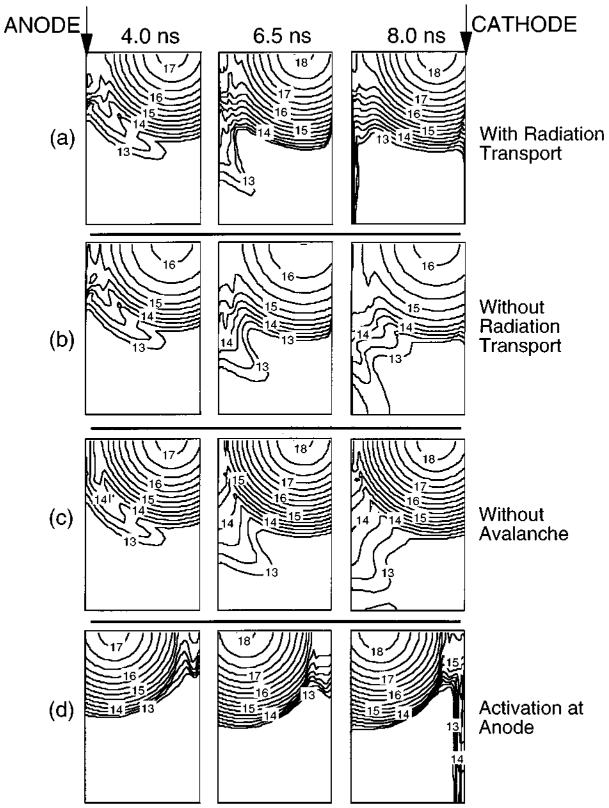

FIG. 5. Time evolution of the electron density for various conditions. The anode is at the left-hand side and cathode at the right-hand side of each frame. Values are shown for only half of the symmetric switch. Time frames are shown from left to right. The contours are labeled with the log (base 10) of the electron density (cm^{-3}). Results are shown for light activation (a) near the cathode with radiation transport, (b) near the cathode without radiation transport, (c) near the cathode without carrier avalanching, and (d) near the anode.

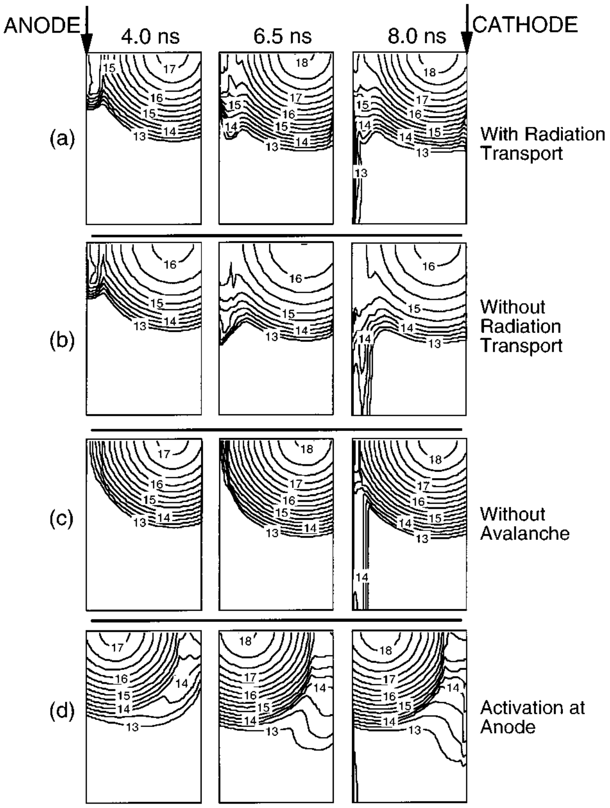

FIG. 6. Time evolution of the hole density. The layout is the same as in Fig. 5. The contours are labeled with the log (base 10) of the hole density (cm^{-3}). Results are shown for light activation (a) near the cathode with radiation transport, (b) near the cathode without radiation transport, (c) near the cathode without carrier avalanching, and (d) near the anode.

cally illuminated switch. The anode is on the left-hand side and the cathode is on the right-hand side of each frame.) At 4 ns (2 ns before the peak of the laser pulse) the electric fields with and without radiation transport appear similar. As the peak of the laser pulse is passed (6.5 ns), the potential without radiation transport is still compressed near the anode producing a large field due to the lack of carriers near the contact. With radiation transport, photogeneration produces carriers near the contact which rapidly avalanche. At 8 ns, the switch without radiation transport still has a large potential drop near the anode; whereas with radiation transport, the potential has completely collapsed. In the absence of the generation of carriers due to the reabsorption of recombination radiation, the electrons traveling at the saturation velocity are not fast enough to cross the switch and collapse the potential near the anode. During their slow transit, their density also decreases due to recombination losses, and the switch ultimately recovers to the open state.

The electron and hole densities are shown in Figs. 5(a) and 6(a), respectively, for light activation near the cathode when radiation transport is included. The electrons are initially swept toward the anode and the holes toward the cathode as they are introduced near the cathode by the laser. Photon transport and reabsorption at the edge of the conductive region produce carriers in regions of high electric field. Avalanche then extends the conductive region. The fact that electron drift is in the direction of propagation of the conductive region gives the false impression the electrons are swept by the field into the anode. Since the speed of propagation of the front is faster than the saturation velocity of the electrons, the majority of apparent motion is due to radiation transport, reabsorption, and avalanche.

The electron and hole densities are shown in Figs. 5(b) and 6(b), respectively, when radiation transport is neglected. The electron density at 6.5 ns is nearly an order of magnitude larger (10^{16} cm^{-3}) near the anode with radiation transport [Fig. 5(a)] compared to when radiation transport is neglected. In the absence of radiation transport, the electrons spread laterally even more, albeit with a smaller density. Radiation transport appears to narrow the electron swarm since avalanche at the edge of the expanding front is preferentially along the axis.

A time evolution of the electric field when intrinsic avalanching of carriers is excluded is shown in Fig. 4(b). The electron and hole densities for these cases are shown in Figs. 5(c) and 6(c), respectively. Avalanche is an important process in moderating large electric fields. The carriers generated by avalanche in regions of high electric field increase the local conductivity, thereby reducing the electric field. Removing

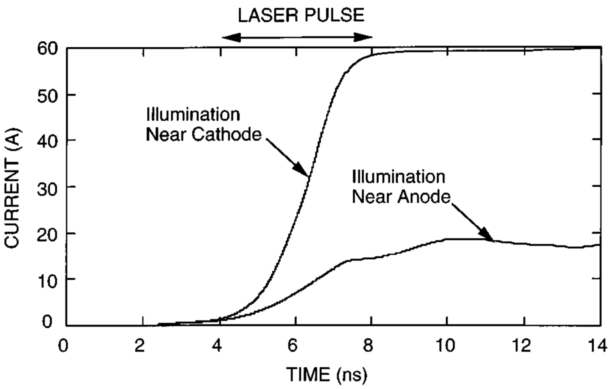

FIG. 7. Current as a function of time for a coplanar intrinsic GaAs switch activated with a spot of light near the cathode and a spot of light near the anode. Activating the switch with a spot of light near the cathode is more effective in closing the switch than activation near the anode. This is due mainly to the lower threshold for avalanching for electrons compared to holes.

avalanche from the model allows the electric field to unconditionally increase near the anode, as seen in Fig. 4(b), which reduces the mobility of the carriers due to velocity saturation. The carriers produced by intrinsic avalanche are essential for rapid switch closure. The electron and hole densities, when intrinsic avalanche is excluded, are similar to those obtained with avalanche in the bulk of the switch. Excess electrons at the anode and excess holes at the cathode typically obtained with avalanche [Figs. 5(a) and 6(a)] are, however, no longer observed.

An investigation was also made into the sensitivity of switch closure on the location of the laser spot. For example, the current through the switch is shown in Fig. 7 for the spot located near the cathode or near the anode. The switch closes more rapidly and conducts more current with laser illumination near the cathode, which agrees with experimental observations by Zutavern *et al.*[2] At 7 ns, the switch activated near the cathode has completely closed, whereas the switch activated near the anode is still in commutation.

The electric field is shown in Fig. 4(c) for laser activation near the anode. In general, the electric field near the cathode does not collapse on the time scale required for rapid switching. Some reduction occurs, but a complete collapse does not. Electric field collapse near both contacts is required for complete switching, as shown in Fig. 3 for a light spot near the cathode. The electron and hole densities for activation near the anode are shown in Figs. 5(d) and 6(d). Even with the electron densities approaching 10^{17} cm^{-3} near the anode, the device does not completely close in the times of interest. Activation near the anode appears to rely primarily on transport of electrons created by photoionization with a smaller contribution from avalanche since the net drift of electrons is toward the anode and not into the region of low conductivity near the cathode. Activation near the cathode produces avalanche in the direction of advance of the photogenerated carriers and onto the low conductivity region. Comparing the electron density for activation near the cathode [Fig. 5(a)] and the hole density for activation near the anode [Fig. 6(d)], there is less production of holes by avalanche near the anode than for that by the electrons near the cathode. This may delay the closing of the switch for the anode triggered case.

The overshoot of the electron velocity at large electric fields plays a minor role in the switching cycle. The voltage characteristic without velocity overshoot (Fig. 2) shows a small delay, however switch closure is still obtained. A time evolution of the electric field when overshoot of electrons is excluded is shown in Fig. 4(d). The electric field produced by large space charge gradients and the spatial nonuniformity of the laser is large enough for avalanche to occur. The larger electric fields which result from the lower conductivity associated with negative differential resistance does not appear necessary to enhance the electric field for intrinsic avalanche to occur.

Two radiation transport effects are not included in the model which may be important to these results. The first is a reduction in the generation of band-gap radiation due to trapping at, for example, EL2 centers. The second is an increased rate of photoionization of these deep traps which might compensate for the reduced photogeneration resulting from filling those traps. For an electron trapping cross section of 5×10^{-15} cm^2,[19] deep trapping competes with direct recombinations when their densities exceed $0.01p$. Since the carrier densities of interest are large (10^{17}–10^{18} cm^{-3}) it is not likely that deep trapping will be important in pure material. The effect of deep traps on radiation transport is an uncertainty and should be addressed in future studies.

IV. CONCLUDING REMARKS

A two-dimensional time-dependent computer model has been used to investigate the commutation in an intrinsic GaAs coplanar pulsed power switch operated in the nonlinear mode and activated with a laser spot. Results from the model show that transport of band-to-band recombination radiation plays an important role in carrier generation and transport in these devices. Reabsorption of radiation is a mechanism that allows carriers to appear to move across the device at speeds greater than their saturation velocities. Reabsorption of the radiation produces carriers in regions of high electric field, leading to avalanche and extension of the high conductivity, low electric field region. This ultimately reduces the electric field at the contacts, which allows for the closing of the switch. In this regard, the method of switch closure is similar to that for streamers in gas phase switches such as spark gaps.[20] The model also predicts that the switch is sensitive to the location of the activating laser pulse. Less laser fluence is required when the laser spot is located near the cathode than near the anode. This may be explained by the larger rate of avalanche by electrons compared to holes. The diffusion model for radiation transport used here is only an approximation, and the effects of deep traps on radiation transport should be investigated. These results suggest a full radiation transport algorithm is warranted to further examine these processes. The nonlinear mode of operation of high power semiconductor switches also produces filamentation of the current across the switch. This three-dimensional effect will also require more sophisticated modeling.

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[1] F. J. Zutavern and G. M. Loubriel, *High-Power Optically Activated Solid-State Switches*, edited by A. Rosen and F. J. Zutavern (Artech House, Boston, 1994), Chap. 11.

[2] F. J. Zutavern, G. M. Loubriel, D. L. McLaughlin, W. D. Helgeson, and M. W. O'Malley, Proc. SPIE **1632**, 152 (1992).

[3] F. J. Zutavern, G. M. Loubriel, M. W. O'Malley, W. D. Helgeson, D. L. McLaughlin, and G. J. Denison, *Proceedings of the 20th IEEE Power Modulator Symposium*, Myrtle Beach, SC, 1992 (IEEE, New York, 1992), p. 305.

[4] G. M. Loubriel, W. D. Helgeson, D. L. McLaughlin, M. W. O'Malley, F. J. Zutavern, A. Rosen, and P. J. Stabile, IEEE Trans. Electron Devices **38**, 692 (1991).

[5] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), Chap. 1.

[6] E. E. Funk, C. C. Kung, E. A. Chauchard, M. J. Rhee, and C. H. Lee, in Ref. 1, Chap. 4.

[7] S. N. Vainshtein, Yu. V. Zhilyaev, and M. E. Levinshtein, Sov. Phys.-Tech. Phys. **31**, 788 (1986).

[8] S. N. Vainshtein, Yu. V. Zhilyaev, and M. E. Levinstein, Sov. Phys. Semicond. **22**, 717 (1988).

[9] Yu. M. Zadiranov, V. I. Korol'kov, V. G. Nikitin, S. I. Ponomarev, and A. V. Rozhkov, Sov. Tech. Phys. Lett. **9**, 280 (1983).

[10] For example, *Session 6, Optically Activated Switching II* [Proc. SPIE **1632** (1992)]; *Session 4, Optically Activated Switching III* [Proc. SPIE **1873** (1993)].

[11] L. Mu and W. R. Donaldson, *Proceedings of the 9th IEEE International Pulsed Power Conference*, edited by K. Prestwich and W. Baker (IEEE, New York, 1993), p. 629.

[12] H. Zhao, P. Hadizad, J. H. Hur, and M. A. Gundersen, J. Appl. Phys. **73**, 1807 (1993).

[13] W. T. White III, C. G. Dease, M. D. Pocha, and G. H. Khanaka, IEEE Trans. Electron Devices **37**, 2532 (1990).

[14] L. Partain, D. Day, and R. Powell, J. Appl. Phys. **74**, 335 (1993).

[15] C. D. Capps, R. A. Falk, and J. C. Adams, J. Appl. Phys. **74**, 6645 (1993).

[16] R. P. Brinkman, K. H. Schoenbach, D. C. Stoudt, V. K. Lakdawala, G. A. Gerdin, and M. K. Kennedy, IEEE Trans. Electron Devices **38**, 701 (1991).

[17] P. J. Stout and M. J. Kushner, J. Appl. Phys. **77**, 3518 (1995).

[18] T. Holstein, Phys. Rev. **72**, 1212 (1947).

[19] S. T. Ko, V. K. Lakdawala, K. H. Schoenbach, and M. S. Mazola, *Proceedings of the Seventh IEEE Pulsed Power Conference*, Monterey, CA, 1989 (IEEE, New York, 1989), p. 861.

[20] S. K. Dhali and P. F. Williams, J. Appl. Phys. **62**, 4696 (1987).