Overshoot in the Response of a Subpicosecond-Pulse-Excited Photoconductor

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Abstract

Experiments designed to observe velocity overshoot in GaAs photoconductors excited by 2.0-eV photons are discussed. Monte Carlo transient velocity computations are presented which indicate that, for 620-nm (2.0-eV) excitation of GaAs, velocity overshoot will not occur for fields less than 20 kV/cm. Photoconductive device model equations are solved numerically for the case of subpicosecond-pulse excitation. The computed photoconductor response is observed to have an overshoot on the picosecond time scale resulting from charge-separation effects. The overshoot behavior is very similar to that observed in measurements of subpicosecond photoconductor response and previously interpreted in terms of velocity overshoot. We conclude that experimentally observed overshoot response at 620 nm is the result of charge-separation effects and not the result of velocity overshoot.

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The study of nonequilibrium-carrier-distribution dynamics on picosecond time scales is of great importance to the development of future generations of semiconductor devices [1,2,3,4]. In this letter, we consider experiments in which a nonequilibrium carrier distribution is optically generated in a photoconductor and the electrical response (specifically, the current) of the photoconductor is measured [5]. One particular characteristic that is sought in these experiments is velocity overshoot [6] resulting from the relaxation of the nonequilibrium carrier distribution.

In the experiments under consideration, a colliding-pulse, mode-locked laser is employed to produce a train of pulses that have durations of a few hundred femtoseconds and photon energies of 2.0 eV. The beam of pulses is split into two beams, with a timing relationship that can be precisely varied. One beam is used for the photogeneration of electron-hole pairs in a semi-insulating, GaAs photoconductor, and the other beam is used in the temporal sampling of the transient photoconductor response. The sampling is performed either with a second photoconductor or with an electrooptic polarizing material. The measured photoconductor response to the subpicosecond optical pulse is interpreted with respect to nonequilibrium carrier dynamics. Recent experiments of this nature have produced an overshoot in the photoconductor response that has been attributed to velocity overshoot [7,8,9]. The observed overshoot occurs on a time scale of a few picoseconds and increases in amplitude with increased bias voltage. This characteristic is similar to theoretical predictions [6] of velocity overshoot. In interpreting these experiments, it is critical to understand the macroscopic, photoconductive-device response characteristics, so that their contribution to the measurements can be accounted for.

In this letter, we present results from Monte Carlo (MC) computations of electron dynamics with initial conditions appropriate for photogenerated electrons. In 1.5-eV photon computations, velocity overshoot becomes prominent for electric fields greater than 5 kV/cm. However, in 2.0-eV computations, velocity overshoot is entirely absent for electric fields up to 20 kV/cm. Thus, photoconductor transient response overshoot resulting from velocity overshoot is not expected in experiments performed with 2.0-eV photons. To account for the observed overshoot in 2.0-eV experiments, we present photoconductive device computational results. These results indicate that an overshoot in the photoconductor response, occurring on a picosecond time scale, resulting from charge separation effects will occur. The amplitude of this overshoot increases with increased bias voltage, and the width of the overshoot decreases with increased excitation intensity. The results of the device computations are in close agreement with experimental observations.

A Monte Carlo method [10] is employed to compute the average transient electron velocity response in a spatially uniform field. The initial carrier distribution in momentum space, just after excitation due to a laser pulse, is determined from the band structure as obtained using a full-zone $\mathbf{k}\cdot\mathbf{p}$ method, which also gives the necessary optical matrix elements. For arbitrary photon energy, the transitions from the heavy hole, light hole, and split-off valence bands result in three separate shells in k-space for the initial states of the excited electrons in the conduction band, with relative weightings determined from k-space integrals of the optical matrix elements. It is important that an accurate band structure, particularly for the hole bands, be used so that the individual contributions to the initial distribution of photoexcited electrons can be accurately determined.

The energy width of the subpicosecond laser pulse combines with an energy width due to lifetime damping (from electron scattering and applied electric field effects) to produce an overall absorption linewidth for each of the three transitions and a resulting spread in the initial k-space distribution. Hole contributions to the transport are disregarded due to their low mobility. In addition, carrier-carrier interactions can be ignored at low laser intensity. The initial k-space distribution of the electrons then evolves under the combined influence of a static electric field and scattering due to acoustic, optical, and intervalley phonons.

Typical velocity transients obtained in this way for a 100-fs pulse incident on GaAs at 300 K are shown in figure 1 for photon energies of 2.0 eV (620 nm) and 1.5 eV (830 nm). For 1.5-eV excitation, in which the electrons are created near $k=0$, velocity overshoot is seen to occur at the higher fields, similar to that reported in MC computations for electrons starting at $k=0$ [6]. For 2.0-eV excitation, however, no velocity overshoot is seen, even up to a field of 20 kV/cm. Computations of the transient in the average electron energy show that velocity overshoot occurs, in most cases, only when the initial average energy is less than the steady state average energy. Correspondingly, the fractional L-valley population monotonically increases towards its steady state value. Because the effective mobility is much higher in the Γ-valley, the time delay for the electrons to reach the L-valley accounts for the velocity overshoot. When there is no velocity overshoot, due to intervalley transfer of the initial electron distribution, the L-valley population quickly becomes greater than its steady state value, to which it subsequently decays. For photon energies above about 1.9 eV, the initial average electron energy is above the energy minimum of the L-valley, and the fast Γ to L intervalley transfer prevents velocity overshoot. Further details of these effects, as seen in MC calculations, are discussed in [11]. It should be stressed that these results are for a spatially uniform electric field — a situation difficult to obtain experimentally. We conclude that velocity overshoot does not account for the observed experimental results. We now explain these results by time-dependent solutions of the macroscopic photoconductive device equations.

The time-dependent modeling of a photoconductor requires the solution of a system of nonlinearly coupled partial differential equations [12,13]. One component of this system of equations is comprised of continuity equations for electron density, hole density, and the density of charge trapped on deep-level sites. The various processes of electron and hole trapping and recombination are modeled by mass-interaction equations. Current transport equations are required to account for the processes of drift and diffusion of electrons and holes. Finally, Poisson's equation is included to account for the effect of charge separation on the electric field. This system of equations is self-consistent and satisfies Maxwell's equations, in that displacement current is correctly accounted for. The most important nonlinear coupling mechanism is between the drift of the electrons and holes under the force of the electric field and the response of the electric field to charge separation.

For most photoconductor geometries and operating conditions, the important spatial variations occur largely in the direction of the applied electric field and, therefore, the system of model equations needs only be solved in one spatial dimension. The solution to the one-spatial-dimension system of equations is found numerically using a finite-difference approach [12,13].

Device-response computations were performed for GaAs photoconductors as a function of gap spacing, bias voltage, excitation duration, and excitation intensity. Figure 2 shows computational results at three different intensities for a photoconductor with a 50-μm gap spacing and with bias voltages of 5 V, 15 V, 25 V, and 50 V. A 100-fs wide, sech^2-shaped excitation pulse with a 50-μm wide Gaussian spatial profile was employed in the computations. The three different intensities, giving the three panels of figure 2, resulted in peak electron and hole densities of 10^{15}, 10^{16}, and 10^{17} cm^{-3}, respectively. To compare the results of the device-response computations with experimental data, the responses presented in figure 2 have been smoothed with a 1-ps, single-pole filter. The smoothing accounts for parasitic effects, such as gap capacitance, and also for the aperture of a sampling device typically used in obtaining the data.

It is seen from figure 2 that an overshoot is present in the response of a photoconductor to sub-picosecond-pulse excitation. The computed photoconductor response is very similar to the measured results presented in references 7–9. The amplitude of this overshoot increases with increasing equilibrium electric field (bias voltage/length) applied to the photoconductor. For excitation intensities increasing by factors of 10, the width of the overshoot is seen to decrease significantly.

The device-response overshoot is the result of charge separation and electric-field relaxation effects in the photoconductor. Electrons and holes, created in pairs by the incident excitation, experience a force in opposite directions that results from the electric field. On the macroscopic scale, this results in charge separation, whereby the region near the hole-attracting contact becomes positively charged with respect to the region near the electron-attracting contact. This results in the collapse of the electric field in the central region of the photoconductor and in the enhancement of the electric field in regions near one or both of the electrical contacts.

Because the device computations presented here do not include finite electron acceleration effects which occur on the picosecond time scale, the current ideally rises to a maximum on the time scale of the laser pulse width. The rise time will, however, be somewhat degraded by the parasitic capacitance of the photoconductor. The rate of electric-field relaxation is slower than the rate at which the photoconductor current rises, but it is faster than the rate of electron and hole loss resulting from trapping, recombination, or sweep-out. Therefore, the current decreases from the maximum at a rate determined by the relaxation of the electric field. The electric field relaxes faster with larger carrier densities because the net charge separation is greater, this results in a smaller relaxation time constant. This effect can be thought of as a high-level-excitation, dielectric relaxation.

The width of the overshoot for the three intensities presented is less than 10 ps and, therefore, this device-response overshoot could be confused with velocity overshoot. The discrimination of device-response overshoot from velocity overshoot could be accomplished through measurements made as a function of excitation intensity and photon energy. In relation to velocity overshoot measurements, it is important to realize that the electric field is relaxing to a highly nonuniform spatial profile on the time scale of the equilibration of the photoexcited carriers. In fact, the electric field may initially be highly nonuniform due to a nonuniform distribution of trapped charge on deep levels in the material. This would generally be the case in a repetitive-pulse experiment because the thermalization time of the deep levels would be greater than the time between pulses.

In conclusion, we have shown that experimentally observed overshoot response for 2.0-ev photons is the result of macroscopic, charge-separation effects which cause electric-field relaxation and not the result of velocity overshoot. In order to observe velocity overshoot in GaAs by experiments like those of references 7–9, it will be necessary to use photon energies significantly less than 2.0 eV. It will also be necessary to reduce the effect of electric-field relaxation.

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FIGURE CAPTIONS

Figure 1 Monte Carlo computations of GaAs electron velocity as a function of time. The initial electron distribution is generated by a 100-fs laser pulse with photon energies of 2.0 eV (top panel) and 1.5 eV (bottom panel). The curves correspond to electric fields of 1 kV/cm (dotted line), 3 kV/cm (dashed line), 5 kV/cm (dot-dash line), and 10 kV/cm (solid line).

Figure 2 Computed device response of a GaAs photoconductor with a 50-μm gap spacing and bias voltages of 5 V, 15 V, 25 V, and 50 V. Panels a, b, and c correspond to excitation intensities producing electron and hole densities of 10^{15}, 10^{16}, and 10^{17} cm^{-3}, respectively.

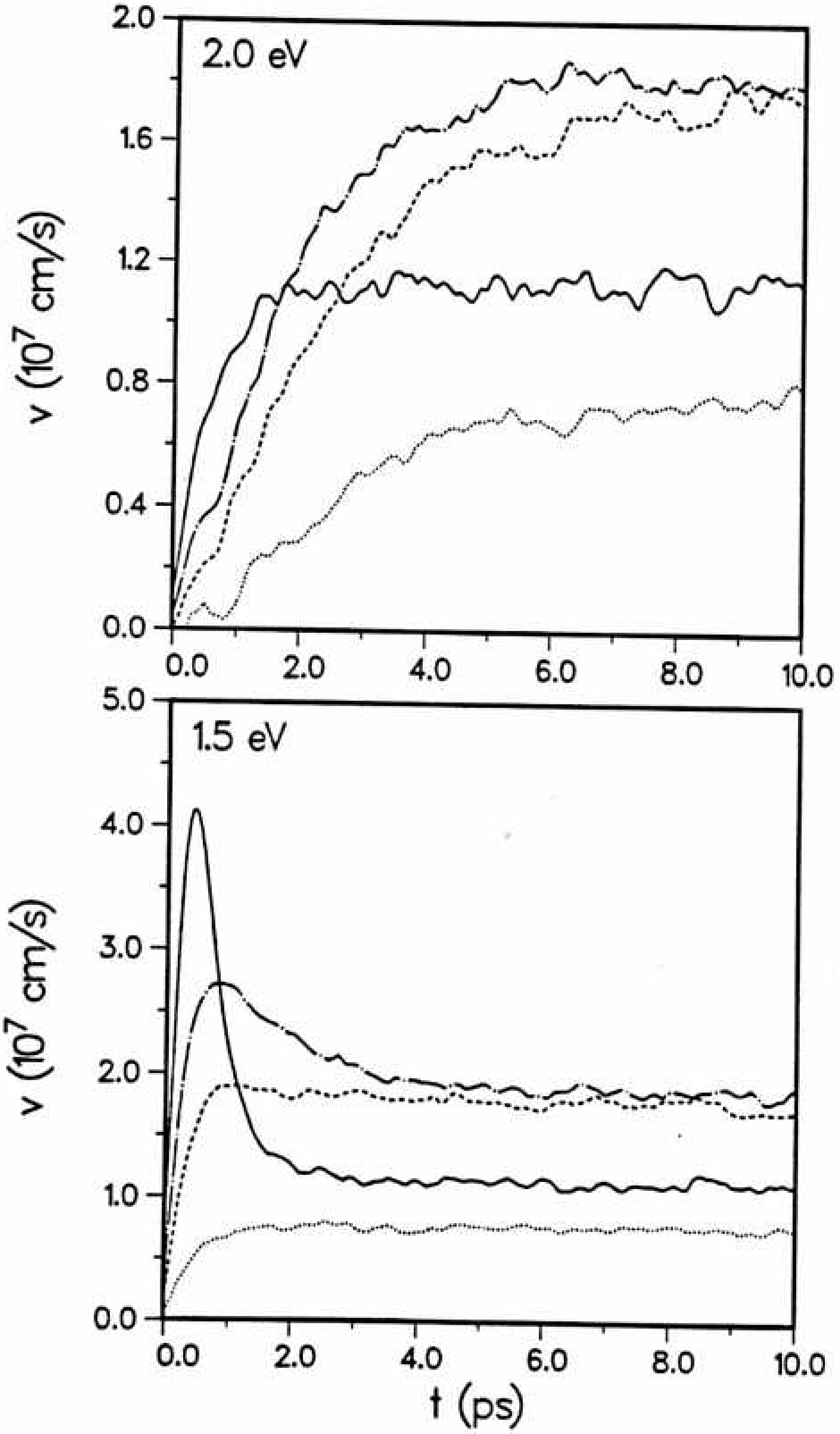
2.0 eV
1.5 eV
v (10^7 cm/s)
v (10^7 cm/s)
t (ps)
0.0
0.4
0.8
1.2
1.6
2.0
1.0
3.0
4.0
5.0
2.0
4.0
6.0
8.0
10.0

Figure 1

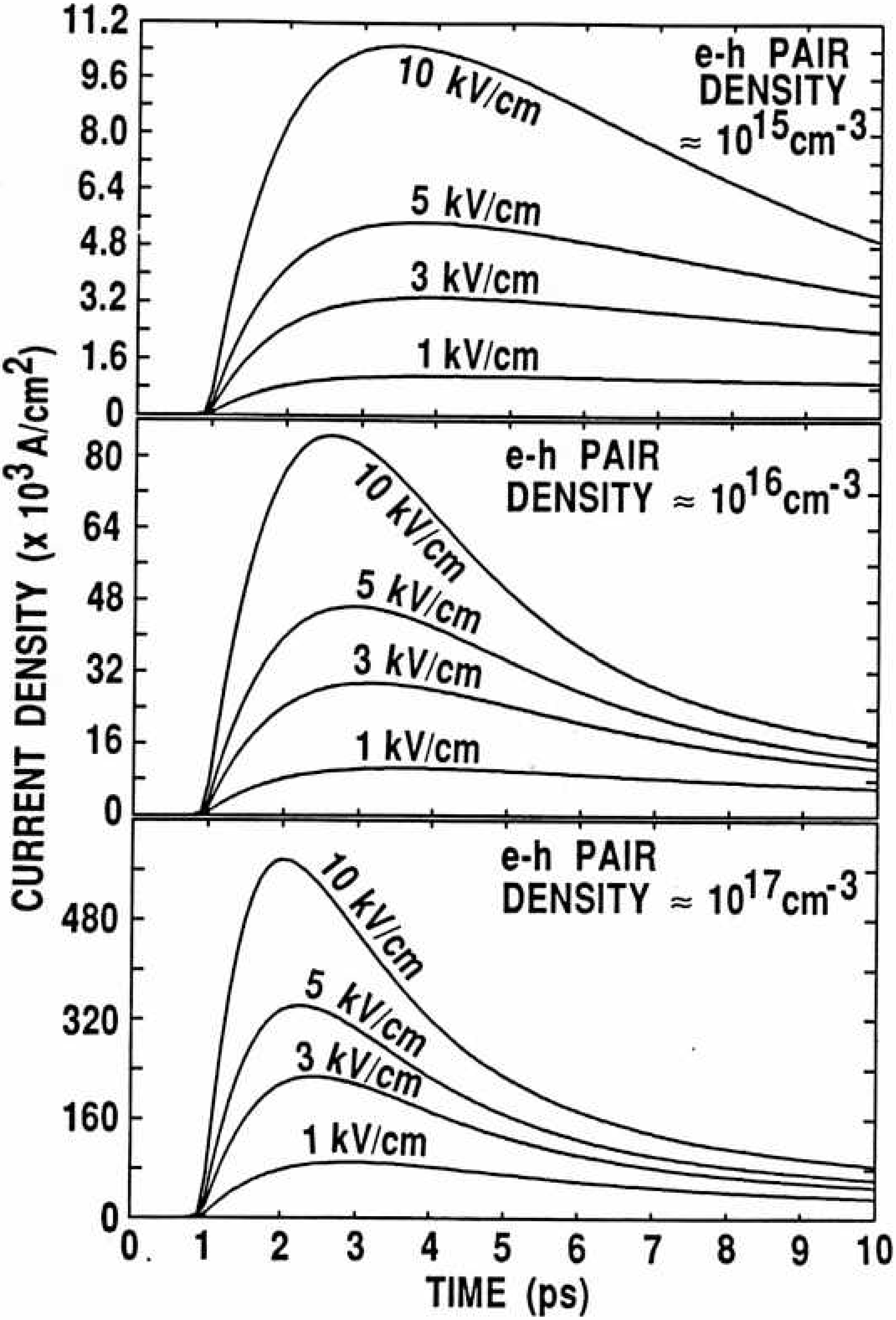
11.2
9.6
8.0
6.4
4.8
3.2
1.6
0
e-h PAIR
DENSITY
≈ 10^15 cm^-3
10 kV/cm
5 kV/cm
3 kV/cm
1 kV/cm
80
64
48
32
16
0
e-h PAIR
DENSITY ≈ 10^16 cm^-3
10 kV/cm
5 kV/cm
3 kV/cm
1 kV/cm
480
320
160
0
e-h PAIR
DENSITY ≈ 10^17 cm^-3
10 kV/cm
5 kV/cm
3 kV/cm
1 kV/cm
CURRENT DENSITY (x 10^3 A/cm^2)
0.
1
2
3
4
5
6
7
8
9
10
TIME (ps)

Figure 2