Effect of carrier-carrier interaction on intervalley transfer rates of photoexcited electrons in GaAs

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(Received 23 December 1988)

The intervalley transfer of carriers photoexcited by a 2.04-eV laser pulse and their response to a 500-V/cm field in GaAs is examined for two excitation levels of 5×10^{16} and 10^{18} cm^{-3}. It is found that the transfer rates are not affected by electron-hole or electron-electron interactions at low excitation levels. At high excitation levels the electron-hole interaction accelerates the return rates to the central valley and provides an important energy-loss channel for the electrons. In response to a 500-V/cm field, the electrons exhibit very small velocities during the first 2 ps. At times beyond 4 ps, the velocities are smaller for higher electron densities.

I. INTRODUCTION

The advent of femtosecond laser pulses has provided an important tool for exploring the dynamics of electrons and holes in semiconductors. During these very short times carrier-carrier interactions, such as the electron-electron (e-e), electron-hole (e-h), and hole-hole (h-h) interactions, intervalley transfer, and hot phonons influence the relaxation of the photoexcited e-h plasma. Several experiments have probed the energy-loss rates of electrons in p-type quantum wells,[1] p-type semiconductors,[2] and the transport of electrons in p-type semiconductors such as GaAs, Si, and $In_xGa_{1-x}As$.[3-5] Additionally, using techniques based on subpicosecond laser pulses, very important material parameters such as the deformation potential for Γ intervalley scattering and transient mobilities in GaAs have been measured.[6-8]

Although the experimental results have shown that the presence of a cold hole plasma can influence the dynamics of electrons in semiconductors, some simple theoretical models which ignore the presence of holes are used to explain the experimental results.[8] The arguments used in such theories are based on the fact that the energy gained by the holes is far less than that of the electrons, the hole mass is much larger than that of electrons, and the holes thermalize very rapidly. Thus it is assumed that examining the electron dynamics is sufficient to provide an understanding of the experimental results. Such approaches ignore the coupling between the electron and hole systems which happens to provide an efficient energy-loss channel for the electrons, especially at high densities and excitation energies.[9] In this paper we discuss how the e-e and e-h interactions influence intervalley transfer rates and the transient response to a 500-V/cm electric field of electrons photoexcited by a 2.04-eV laser pulse in GaAs. The details of the Monte Carlo model and the theory of e-h interaction have been published elsewhere.[9]

II. INTERVALLEY TRANSFER RATES

The effect of e-h and e-e interactions on the intervalley transfer rates of electrons photoexcited by a 2.04-eV laser pulse was examined for excitation levels of 5×10^{16} and 10^{18} cm^{-3}. The electron population in each of the three conduction-band valleys is shown in Fig. 1 for an excitation level of 10^{18} cm^{-3}. From this figure, it is obvious that immediately after excitation the electron population in the central valley drops sharply to 20% after 300 fs. The transfer out of the central valley is not affected by introducing the e-e or the e-h interactions. However, the transfer to the X valley is enhanced by the e-e interaction as can be seen in Fig. 1(c). This is due to the fact that the fraction of electrons at high-energy tails, where they can scatter to the X valley, is increased as a result of e-e interaction. On the other hand, the return of electrons from the upper valleys to the central valley is enhanced when e-h interaction is included. For example, the population of electrons in the L valley decreases to 50% after 3 ps when only the e-e and e-ph interactions are considered. When the e-h interaction is included, the population drops to 30% after 3 ps as can be seen in Fig. 1(b). The population of electrons in the central valley when the e-h interaction is taken into account is about 10% larger after 8 ps compared to the situation where it is not included, as can be seen in Fig. 1(a).

The time dependence of the energy of the electrons relative to the conduction-band edges in the Γ and L valleys are plotted in Fig. 2(a). The figure shows that the electrons in the central valley cool down faster when the e-h interaction is included, which is consistent with the increased energy-loss rates of the electrons through e-h interaction at higher concentrations and energies. The e-e interaction leads to a minor increase in the cooling rate especially during the first 4 ps. This is due to the fact that the electrons which end up at high-energy tails as a result of e-e scattering lose energy primarily through the unscreened interaction with intervalley phonons. In our earlier calculations the e-e interactions reduced the cooling rates of electrons photoexcited with excess energies well below the Γ-L energy gap separation.[9] Under such conditions the electrons at the high-energy tails lose energy via the strongly screened interactions with LO phonons. The cooling of the electrons in the L valley is fast, and is slightly enhanced by the presence of e-h interac-

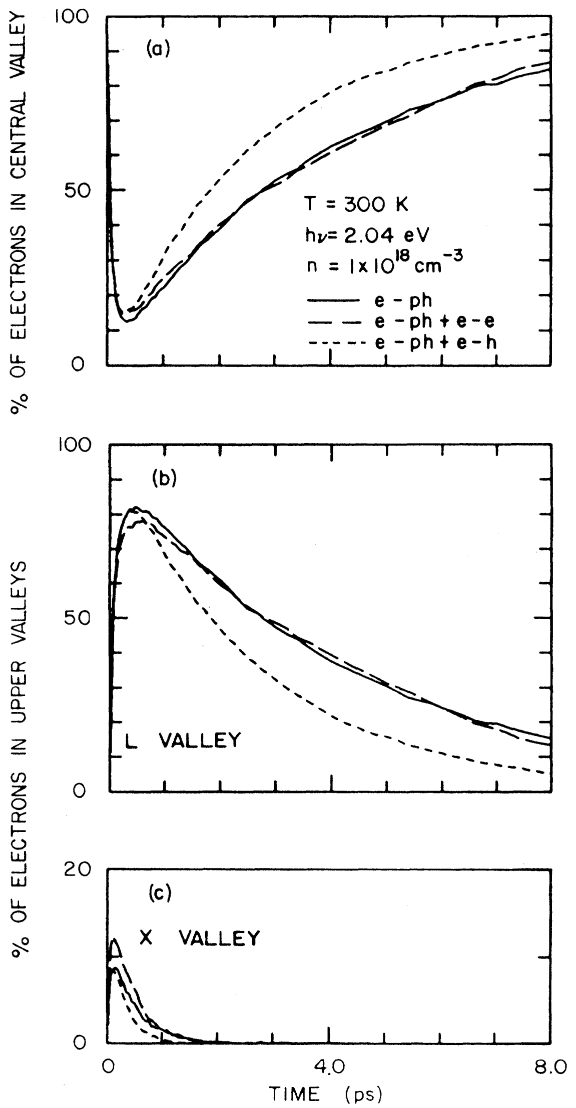

FIG. 1. Time evolution of the electron population in the (a) *P* valley, (b) *L* valley, and (c) *X* valley.

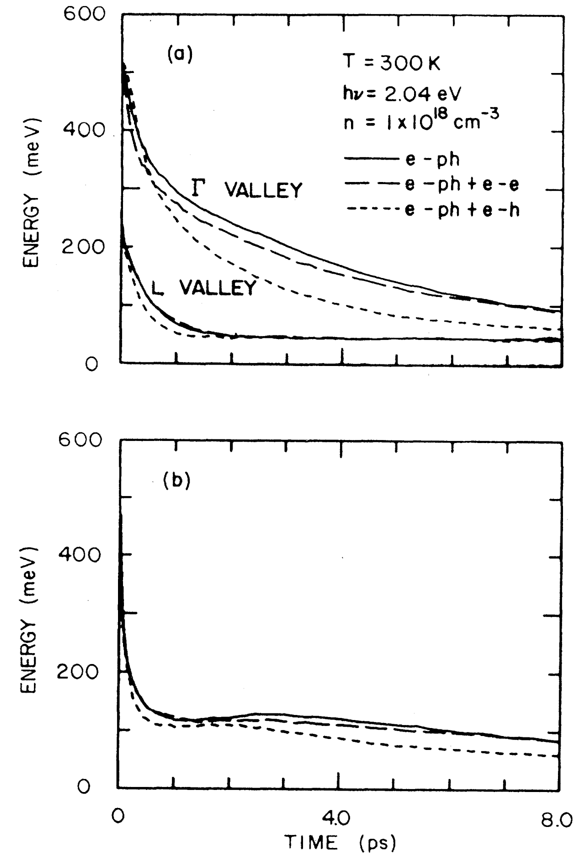

FIG. 2. Time evolution of the kinetic energy of the electrons (a) in Γ and *L* valleys and (b) as an average kinetic energy.

tions. This follows from the fact that the primary energy-loss mechanisms for electrons in the *L* valley are the interactions with the intravalley and intervalley optical phonons which are not screened.[10]

The average kinetic energy of the whole electron ensemble is plotted in Fig. 2(b). Notice that the average kinetic energy drops rapidly during the first picosecond as a result of the electron transfer to the upper valleys and then stays very flat up to 2 ps after the excitation. This is followed by an increase in the average kinetic energy as a result of the return of the electrons to the Γ valley from the upper valleys since the kinetic energy of each returning *L* valley electron is about 300 meV. The increase occurs earlier when the *e-h* interaction is included than when it is ignored. This is consistent with the fact that the *e-h* interaction accelerates the return rate of electrons from the upper valleys to the central valley [see Fig. 1(a)]. Additionally, the average energy is always smaller when the *e-h* interaction is included because of the energy lost by the electrons through *e-h* interaction. On the other hand, including *e-e* interaction reduces the kinetic energy by a small amount during the time interval between 2 and 5 ps after excitation compared to the situation where only the *e*-ph interaction is considered. During this period, a small fraction of electrons that undergo *e-e* scattering move to higher-energy states where their relaxation is dominated by the unscreened and strong intervalley and intravalley deformation potential scattering. At longer times the average kinetic energy is the same whether *e-e* scattering is included or not, because the majority of the electrons reside in the central valley at lower-energy states.

The simulation was then repeated at a lower excitation level of 5×10^{16} cm^{-3}. The variation of the population of the central valley and the average energy of the electrons are plotted in Figs. 3(a) and 3(b), respectively. The plots show that neither *e-h* nor *e-e* interactions affect the transfer rates or the energy relaxations in a significant way. This is because at this low concentration the *e*-ph interactions are the dominant scattering processes and provide the most effective energy-loss channel.[9] Howev-

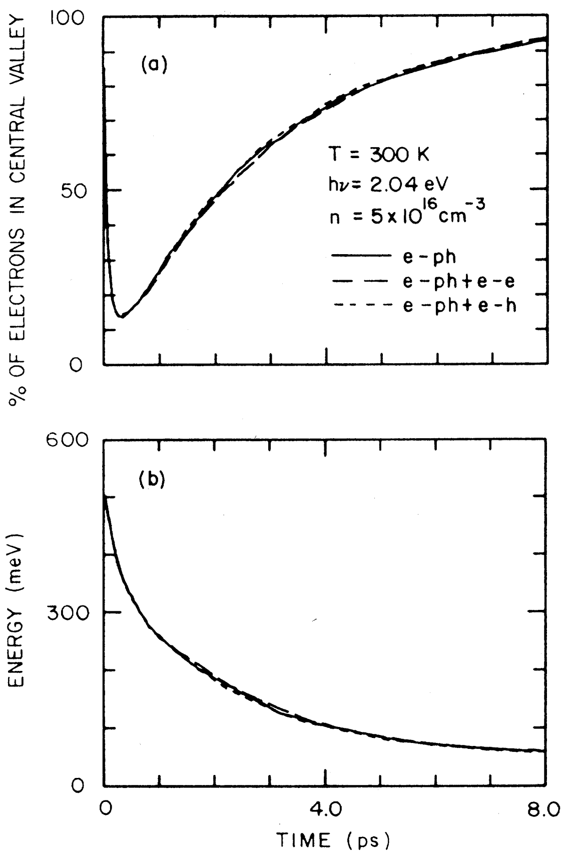

FIG. 3. Time evolutions of (a) electron population and (b) electron energy in the central valley.

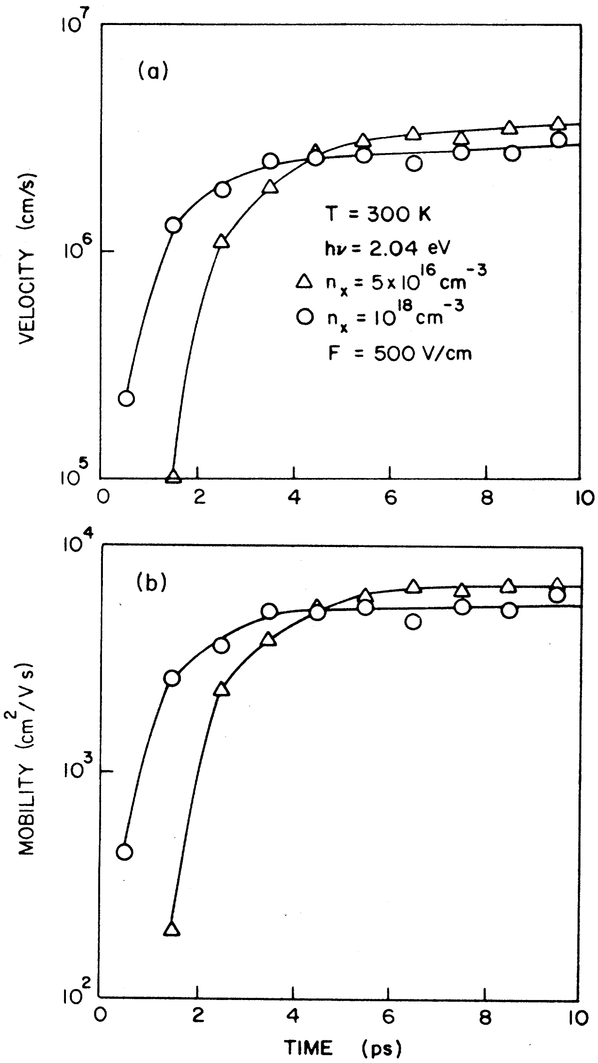

FIG. 4. Time dependence of (a) transient velocity and (b) transient mobility of the photoexcited electrons (each data point is averaged over 1 ps).

er, overall, the transfer rates back to the central valley and cooling rates are faster at an excitation level of 5×10^{16} cm^{-3} compared to that at 10^{18} cm^{-3} when the *e-h* interaction is ignored. This is due to the strong screening of the LO-phonon scattering at high electron concentration which reduces the rate at which electrons lose energy by LO-phonon emission.[9] When the *e-h* interaction is included, the rate at which electrons return to the central valley and lose energy is slightly faster at the higher excitation level because the increased rate at which electrons lose energy through *e-h* interaction offsets the reduction in the rate at which they lose energy via LO-phonon emission at high densities.

III. RESPONSE TO ELECTRIC FIELDS

The response of the photoexcited electrons to a uniform 500-V/cm electric field was investigated for excitation levels of 5×10^{16} and 10^{18} cm^{-3} for a 2.04-eV laser pulse. The time dependence of the transient velocities of the electrons for these excitation levels are plotted in Fig. 4(a). In this figure each data point represents an average over a 1-ps time interval to minimize the fluctuation. Notice that the velocities for all of the excitation levels are very small during the first 2 ps. This is because during this time interval the dominant scattering mechanism is the momentum-randomizing intervalley and intravalley deformation potential scattering. Within this period the magnitudes of the velocities are higher for higher excitation levels due to the increase in the *e-h* scattering events at the expense of the LO-phonon scattering which is strongly screened at high excitation levels. This leads to a higher electron population in the central valley and more frequent smaller-angle scattering at high densities because the *e-h* interaction yields more smaller-angle scattering than LO-phonon scattering. After the first 2 ps the population of the electrons in the central valley increases and the velocity increases sharply for an excitation level of 5×10^{16} cm^{-3}. For higher densities the increase is gradual. However, the velocity for an excitation level of 1×10^{18} cm^{-3} is larger than that at 5×10^{16} cm^{-3} up to 4 ps, after which it is slightly smaller.

The experimental measurements of transient mobility in GaAs by Nuss and co-workers[8] revealed that during the first 2 ps the mobilities were very small. The mobilities then increased gradually and were always smaller for higher electron densities. To facilitate the comparison between the experimental results and our calculations, we have plotted the mobilities in Fig. 4(b). Note that because the electron system is far from equilibrium during this time interval, the equilibrium relationship between the velocity, field, and mobility is not a good approximation. There is a qualitative agreement between the experiment and the results for times shorter than 2 ps, during which the mobilities are very low, and at times beyond 4 ps, during which the mobilities for an excitation level of 1×10^{18} cm^{-3} are smaller than that at 5×10^{16} cm^{-3}. During the intermediate times the calculated mobilities are larger for higher electron concentrations because of the large fraction of the electrons that return to the central valley and the screening of electron–LO-phonon interactions. The complicated structure of the valence band which leads to anisotropic behavior of the hole effective mass is reflected in the experimental results. Furthermore, holes at higher-energy states have larger effective masses which are not included in this calculation. A more realistic calculation at low fields including the nonuniform distribution of the photoexcited electrons can give better agreement with the experimental results.

IV. SUMMARY

In this paper we have shown that the *e-h* interaction accelerates the return rates of electrons to the central valley at high densities. The *e-e* interaction enhances transfer rates to the X valley and increases the energy-loss rates of electrons by a small amount. This leads to higher transient velocities at higher densities during the first 4 ps following the excitation. At longer times the velocities are smaller for higher densities. The calculated mobilities are in qualitative agreement during the first 2 ps and at times beyond 4 ps.

ACKNOWLEDGMENTS

This work was supported by the U.S. Office of Naval Research.

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