Energy-Loss Rates for Hot Electrons and Holes in GaAs Quantum Wells

Jagdeep Shah
AT&T Bell Laboratories, Holmdel, New Jersey 07733

and

A. Pinczuk, A. C. Gossard, and W. Wiegmann
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 23 October 1984)

We report the first direct determination of carrier-energy–loss rates in a semiconductor. These measurements provide fundamental insight into carrier-phonon interactions in semiconductors. Unexpectedly large differences are found in the energy-loss rates for electrons and holes in GaAs/AlGaAs quantum wells. This large difference results from an anomalously low electron-energy–loss rate, which we attribute to the presence of nonequilibrium optical phonons rather than the effects of reduced dimensionality or dynamic screening.

PACS numbers: 73.40.Lq, 72.20.Jv

The interaction of electrons and holes with phonons plays a central role in the physics of semiconductors. These interactions are also important in hot-electron physics, which determines the behavior of carriers under high electric fields and hence the characteristics of ultrasmall, high-field devices. There is considerable current interest in how these interactions are modified (1) in the presence of high density of carriers and (2) when these carriers are confined to two dimensions, as in quantum wells or heterostructures. Mobility measurements, while useful in many ways, provide only limited information about carrier-phonon interactions because mobilities are also influenced by elastic collisions (e.g., impurity scattering). In contrast, carrier-energy–loss rates provide fundamental insight into carrier-phonon interactions because they are directly related to inelastic collisions with the phonons.

In recent years, picosecond excite-and-probe[1,2] and luminescence experiments[3,4] have been used to measure cooling curves for the photoexcited hot electron-hole plasma. Such experiments show that the cooling of the plasma is slower than expected. The carrier-energy–loss rates have been deduced from such measurements by comparison of the measured cooling curves with calculated curves. However, the simultaneous presence of electrons and holes complicates the interpretation of these experiments. The nonlinear luminescence experiment[5] suffers from the additional problem that the information is derived from relaxation times at a few discrete wavelengths and from time-integrated spectra. Furthermore, these experiments[2,4,5] have generated conflicting results and interpretations regarding the influence of reduced dimensionality and plasma density on carrier-energy–loss rates.

We report in this Letter a direct determination and the first comparison of the electron and hole energy-loss rates in a semiconductor. The most striking result of our studies is that the low-temperature carrier-energy–loss rate for electrons is 25 times smaller than for holes in GaAs quantum wells. We show that this surprisingly large difference results from an anomalously low electron-energy–loss rate. Our analyses indicate that, in contrast to recent suggestions,[4] the effects of reduced dimensionality, dynamic screening, and degenerate electron statistics are not expected to reduce the electron-energy–loss rate. We attribute the reduction in the electron-energy–loss rate primarily to a large nonequilibrium optical phonon population (i.e., hot phonons) resulting from the long (5 psec[6]) phonon lifetime. The magnitude of the reduction and its variation with electron temperature are explained by a model calculation. Hole-energy–loss rates are not significantly affected by hot-phonon effects, as discussed below. Our results imply that the reduction in the cooling of a two-dimensional (2D) electron-hole plasma in high-excitation picosecond experiments cannot be attributed to reduced dimensionality, in contrast to some current conclusions.[4,5]

These determinations were made by a combination of optical and electrical techniques. We simultaneously measured the luminescence spectra, which yield carrier temperatures, and the *I-V* characteristics, which yield the power input per carrier, both as a function of an applied electric field.[7] *Since, in a steady state, the power input from the electric field must equal the power loss from the carriers to the lattice, this technique provides a unique means of directly determining the carrier-energy–loss rates to the lattice as a function of the carrrier temperature.*

One *p*-type and two *n*-type samples of modulation-doped GaAs/AlGaAs multiple-quantum-well heterostructures grown by molecular-beam epitaxy were investigated. The samples were fabricated into Hall bridges and were immersed in superfluid He. The central part of the bridge was excited with a weak

(< 10 mW/cm^2) dye-laser beam (≈ 7700 Å). The luminescence from the sample and the current-voltage characteristics were measured simultaneously for electric fields (F) applied parallel to the heterolayers. For $F > 40$ V/cm, the field was pulsed (1–3-μsec-wide pulses, period > 25 μsec), and only the luminescence during the pulse was measured.

Luminescence from the samples results from intrinsic recombination of photoexcited minority carriers with the 2D majority carrier plasma present in the GaAs quantum wells.[7–9] Near the band-gap energy, these spectra show structure which is attributed to the contribution of several conduction and valence subbands to emission. For the present investigations, we focus on the spectral high-energy tail where the emission intensity decreases exponentially with photon energy (see inset in Fig. 1). This behavior shows[10] that the carriers can be characterized by a Fermi-Dirac distribution function with a temperature T_c higher than the lattice temperature T_L. The inset of Fig. 1 shows that T_c in the n-type sample considerably exceeds T_c in the p-type sample for comparable fields.[11]

In Fig. 1 we plot $1/T_c$ as a function of energy-loss rate per carrier for all three samples. The energy-loss processes in 3D are dominated by acoustic phonons for $T_c < 30$ K and by optical phonons above ~ 35 K.[10] The slopes of the $1/T_c$ versus power-loss curves in Fig. 1 in the linear region are close to the optical phonon energies (33–37 meV) in GaAs. Thus optical phonons dominate for 2D electrons and holes, even in the presence of a relatively high-density plasma. Another important feature of the data is that the curve for electrons bends over and approaches the curve for holes at higher T_c. The most striking conclusion from Fig. 1 is that *the holes remain considerably cooler than the electrons and that the energy-loss rate at any given $T_c < 100$ K is a factor of 25 larger for holes than for electrons.* This is the first quantitative comparison of electron and hole energy-loss rates in a semiconductor.

The carrier-energy–loss rates are related to the average carrier-phonon scattering rates. For electrons, these rates are determined by scattering with longitudinal optical phonons via the wave-vector dependent Fröhlich interaction. For holes, one must also consider the wave-vector–independent deformation-potential interaction with both longitudinal and transverse optical phonons.[12] In order to interpret our results, we first consider the effect of carrier confinement on these scattering rates.[13–17] In the absence of a plasma, the relevant parameter in comparing the 2D and the 3D scattering rates is $E_0/\hbar\omega_0$, where $E_0 = \pi^2\hbar^2/2m^* d_1^2$ is the confinement energy of the quantum well and $\hbar\omega_0$ is the optical phonon energy.[17] In our case, where $E_0/\hbar\omega_0$ is approximately 0.25 for all three samples investigated, the calculations[17] show that the 2D scattering rates are the same as 3D rates at high carrier energies ($> 2\hbar\omega_0$) but slightly exceed the 3D rates at lower energies. Thus the average electron-phonon scattering rates in 2D are approximately the same as the corresponding 3D rates. In Fig. 1 we have plotted as a dashed line the known variation[10] of the 3D electron-energy–loss rate with electron temperature. We immediately conclude that the measured low-temperature electron-energy–loss rates are approximately a factor of 8 smaller than expected for 2D electrons.

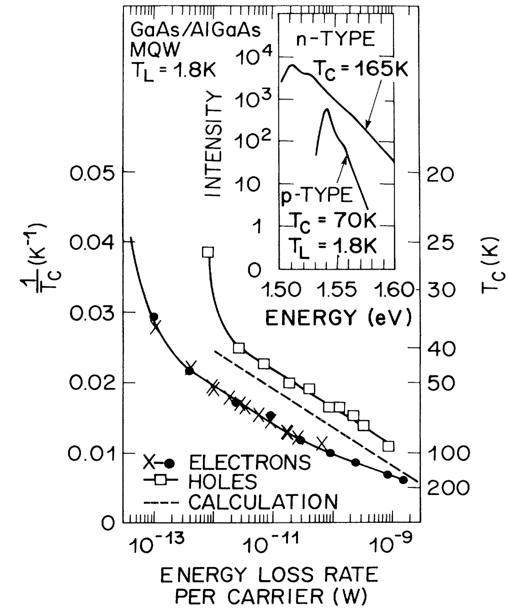

FIG. 1. Inverse of carrier temperature ($1/T_c$) vs energy-loss rate per carrier to the lattice for one p-type and two n-type modulation-doped samples of GaAs/Al$_x$Ga$_{1-x}$As multiple-quantum-well heterostructures. Sample 1: $n = 7\times10^{11}$, $x = 0.2$, $d_1 = 262$, $d_2 = 317$, $d_3 = 163$, $\mu = 63\,000$, $\eta = 20$. Sample 2: $n = 3.9\times10^{11}$, $x = 0.23$, $d_1 = 258$, $d_2 = 284$, $d_3 = 118$, $\mu = 79\,000$, $\eta = 15$. Sample 3: $p = 3.5\times10^{11}$, $x = 0.45$, $d_1 = 94$, $d_2 = 43$, $d_3 = 256$, $\mu = 36\,000$, $\eta = 15$. n and p are density (inverse squared centimeters) per GaAs layer; d_1, d_2, and d_3 are thicknesses of GaAs, doped AlGaAs, and undoped AlGaAs spacer layers (in angstroms), respectively; μ is mobility (cm^2/V·sec); and η is number of periods. Points are experimental (crosses for sample 1, circles for sample 2), solid curves are drawn to guide the eye, and the dashed line is calculated for nondegenerate 3D electron gas. Inclusion of degeneracy does not affect the calculated curve significantly. The inset shows typical luminescence spectra at $T_L = 1.8$ K for samples 1 and 3 at 750 V/cm and 1000 V/cm, respectively. Values of T_c deduced from the spectra are also shown.

We now consider what is expected for holes. On the basis of the detailed calculation of hole-phonon scattering rates in 3D,[18] we estimate that, in 3D systems, the hole-phonon scattering rates are 2.5 to 3 times larger than the rates for electrons when deformation-potential interaction is included for the holes. The arguments given in the preceding paragraph lead us to expect that the hole-energy–loss rates are comparable in 2D and 3D, if we ignore the added complexities of valence bands in 2D.[19,20] Thus we conclude that the measured hole-energy–loss rates (Fig. 1) agree quite well with the energy-loss rates expected for 2D holes.

These considerations show that the large difference between the rates for electrons and holes results from an anomalously low electron-energy–loss rate. We consider first two factors that may contribute to this result. The first is the effect of reduced dimensionality on the optical phonons of the GaAs layers[19] and the second is the effect of the high-density plasma on the polar phonon coupling to electrons. Energy and momentum conservation shows that the in-plane phonon wave vectors q involved in energy-loss processes are $q > 10^6$ cm^{-1} so that $qd_1 > 1$. Therefore the slab modes that describe the optical phonons in the GaAs layers have 3D character and are unlikely to make 2D scattering rates much different from 3D rates.

In the presence of the high-density plasma, one has to consider dynamic screening effects, i.e., the scattering of the carriers occurs by interaction with the coupled 2D-plasma–LO-phonon modes of the layers.[21] The wave vectors q relevant in the electron-energy–loss rate are in the range $(1\text{–}6)\times 10^6$ cm^{-1}. For $q < 2.5\times 10^6$ cm^{-1}, the lower-energy (plasmalike) mode is Landau damped and will not contribute to the electron-energy–loss rate. However, the higher-energy (phononlike) mode is not Landau damped in this wave-vector range and we expect an enhancement of the scattering rate. For q somewhat larger than 2.5×10^6 cm^{-1}, both modes are Landau damped and this will lead to some reduction in the scattering rate. For $q > 2k_F$ (where k_F is the Fermi wave vector, $\simeq 2\times 10^6$ cm^{-1}), the coupling between the LO phonons and the high-density plasma need no longer be considered and the electron scattering rate approaches that due to bare phonons. Similar conclusions may be deduced from the calculations by Price.[22] These considerations indicate that the dynamic screening is not the cause of the anomalously low electron-energy–loss rates. The fact that the electron-energy–loss rate approaches the expected value at higher T_c (Fig. 1) provides experimental evidence against dynamic screening, since it is not so strongly temperature dependent in the degenerate electron system.

We propose that nonequilibrium population of optical phonons in excess of what is expected at the lattice temperature is responsible for the anomalously low electron-energy–loss rates. Such hot phonons[23] have been invoked previously[24,25] for explaining the slow cooling of 3D photoexcited electron-hole plasma in picosecond experiments. In 2D heterolayers, acoustic phonons generated by electric field heating of carriers have been measured.[26] Price[27,28] has treated the theoretical problem of hot acoustic and optical phonons in semiconductor heterolayers.

We have estimated the effects of hot phonons on electron-energy–loss rates by making a model calculation for 3D electrons characterized by T_c. A 3D calculation is adequate because the scattering rates in 2D and 3D are approximately the same, as discussed above. The nonequilibrium optical phonons are described by a temperature T_q such that the occupation factor for the phonons at q is $N(T_q)=1/[\exp(\hbar\omega_0/kT_q)-1]$. The generation rate for phonons of wave vector q is calculated for the Fröhlich electron-phonon interaction by integration over electron energy E of the well-known expressions[11] for the probability of scattering of a phonon of wave vector q by an electron of energy E. $N(T_q)$ for phonons is then obtained for each q by the equating of this generation rate with the phonon decay rate given by $[N(T_q)-N(T_L)]/\tau_q$, where τ_q is the phonon lifetime and $N(T_L)$ is the Bose-Einstein phonon occupation factor at the lattice temperature. We find that for a density of 2×10^{17} cm^{-3}, $\hbar\omega_0 = 36.8$ meV, $T_c = 50$ K, and $\tau_q = 5$ psec, the phonon temperatures T_q are 45, 49.5, and 33 K at $q = 1.25\times 10^6$, 2.5×10^6, and 5×10^6 cm^{-1}, respectively. Since the electron-energy–loss rate due to interaction with phonons of wave vector q decreases as T_q approaches T_c,[29] the rate will be clearly smaller in the case considered above compared to the case when the optical phonons are in equilibrium with the lattice at T_L. In fact, by integrating over q, we find that the electron-energy–loss rate is reduced by a factor of 7 at $T_c = 50$ K, in reasonably good agreement with the data in Fig. 1. For higher T_c, the reduction is smaller because $N(T_c)$ is larger. This trend is accentuated because of the reduction in τ_q with increasing T.[6] Thus, the experimental determination (Fig. 1) that the electron-energy–loss rate approaches the expected value at higher T_c is also in accord with the hot-phonon model. The effect of hot phonons on hole-energy–loss rate is rather small because of the large phonon wave vectors (with correspondingly large phase space) involved in hole scattering and also because of the wave-vector–independent deformation-potential scattering.

In conclusion, by using a combination of electrical and optical techniques, we have made a *direct and separate* determination of the electron and hole energy-loss rates to the lattice as a function of carrier temperature in GaAs/AlGaAs heterostructures. This is the first time that these rates, which are governed by inelastic collisions with phonons, have been quantitatively determined in a semiconductor. We found an unexpectedly large difference between the electron and hole energy-loss rates. Whereas the rates for holes agree with theoretical expectations the rates for electrons are anomalously low. Analysis indicates that the effects of reduced dimensionality and dynamic screening on optical phonon scattering rates are small and nonequilibrium optical phonon population is the primary cause for the low electron-energy–loss rate.

We thank H. L. Störmer for fruitful discussions and G. D. Aumiller, K. Baldwin, and A. E. DiGiovanni for technical assistance.

[1]C. V. Shank, R. L. Fork, R. F. Leheny, and Jagdeep Shah, Phys. Rev. Lett. **42**, 112 (1979); R. F. Leheny, Jagdeep Shah, R. L. Fork, C. V. Shank, and A. Migus, Solid State Commun. **31**, 809 (1979).

[2]C. V. Shank, R. L. Fork, R. Yen, J. Shah, B. I. Greene, A. C. Gossard, and C. Weisbuch, Solid State Commun. **47**, 981 (1983).

[3]Kathleen Kash and Jagdeep Shah, Appl. Phys. Lett. **45**, 401 (1984).

[4]J. F. Ryan, R. A. Taylor, A. J. Tuberfield, A. Maciel, J. M. Worlock, A. C. Gossard, and W. Weigmann, Phys. Rev. Lett. **53**, 1841 (1984).

[5]Z. Y. Xu and C. L. Tang, Appl. Phys. Lett. **44**, 692 (1984).

[6]R. K. Chang, J. M. Ralston, and D. E. Keating, in *Proceedings of the International Conference of Light Scattering Spectra of Solids,* edited by G. B. Wright (Springer-Verlag, New York, 1969), p. 369.

[7]Jagdeep Shah, P. Pinczuk, H. L. Störmer, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **42**, 55 (1983).

[8]A. Pinczuk, Jagdeep Shah, R. C. Miller, A. C. Gossard, and W. Wiegmann, Solid State Commun. **50**, 735 (1984).

[9]Jagdeep Shah, A. Pinczuk, H. L. Störmer, A. C. Gossard, W. Wiegmann, in Proceedings of Seventeenth International Conference on Physics of Semiconductors, San Francisco, 1984 (to be published).

[10]Jagdeep Shah, Solid State Electron. **21**, 43 (1978), and J. Phys. Paris, Colloq. **42**, C7-445 (1981).

[11]Large differences in collection of electrons and holes in narrow quantum wells were deduced from photopumping experiments and attributed to smaller hole velocities resulting from larger mass. R. D. Dupuis, P. D. Dapkus, R. M. Kolbas, N. Holonyak, Jr., and H. Shichijo, Appl. Phys. Lett. **33**, 596 (1978). Also, R. Chin, N. Holonyak, Jr., S. W. Kirchoefer, R. M. Kolbas, and E. A. Rezek, Appl. Phys. Lett. **34**, 862 (1979).

[12]See, for example, E. M. Conwell, *High Field Transport in Semiconductors* (Academic, New York, 1967).

[13]D. K. Ferry, Surf. Sci. **75**, 86 (1978).

[14]K. Hess, Appl. Phys. Lett. **35**, 484 (1979).

[15]P. J. Price, Ann. Phys. (N.Y.) **13**, 217 (1981).

[16]B. K. Ridley, J. Phys. C **15**, 5899 (1982).

[17]F. A. Riddoch and B. K. Ridley, J. Phys. C. **16**, 6971 (1983).

[18]M. Costato and L. Reggiani, Phys. Status Solidi (b) **58**, 47 (1973).

[19]J. E. Zucker, A. Pinczuk, D. S. Chemla, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **53**, 1280 (1984).

[20]R. Sooryakumar, D. S. Chemla, A. Pincquk, A. C. Gossard, W. Wiegmann, and L. J. Sham, in Ref. 9.

[21]E. Burstein, A. Pinczuk, and D. L. Mills, Surf. Sci. **98**, 451 (1980).

[22]P. J. Price, J. Vac. Sci. Technol. **19**, 599 (1981).

[23]Jagdeep Shah, R. C. C. Leite, and J. F. Scott, Solid State Commun. **8**, 1089 (1970).

[24]J. Collett, A. Cornet, M. Pugnet, and T. Amand, Solid State Commun. **42**, 883 (1982).

[25]W. Pötz and P. Kocevar, Phys. Rev. B **28**, 7040 (1983).

[26]M. A. Chin, V. Narayanamurti, H. L. Störmer, and A. C. Gossard, in Ref. 9.

[27]P. J. Price, in Ref. 9.

[28]P. J. Price, Superlattices Microstructures **1**, 255 (1985).

[29]Sh. M. Kogan, Fiz. Tverd. Tela (Leningrad) **4**, 2474 (1963) [Sov. Phys. Solid State **4**, 1813 (1963)].