Hot-Electron Relaxation in GaAs Quantum Wells

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We report experiments in which we determine the rate of LO-phonon emission by hot electrons. High-energy tails of the photoluminescence spectra are used to measure the distributions of hot electrons, which are heated both optically and electrically. Comparison of resultant temperatures shows that virtually all the excess kinetic energy of an optically excited electron-hole pair stays in the electron system. Both this result and an analysis of the spectra themselves show that electron scattering is much faster than LO-phonon emission. The measured LO-phonon emission rate is in agreement with theory. Hot phonons do not appear to play an important role in our experiments.

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Over the last several years, there has been a sustained interest in the behavior of hot electrons and hot holes in semiconductors.[1] This interest springs in part from curiosity about fundamental interactions (electron-phonon coupling and electron-electron scattering, for example), but it is supported also by the necessity to understand devices in which carriers are heated either inadvertently or purposely.

Recently, much of the interest in hot carriers has been focused on two-dimensional (2D) systems. 2D hot-carrier devices have been proposed[2] and demonstrated,[3] and much effort has been expended to understand 2D hot-carrier transport in metal-oxide-semiconductor field-effect transistors and analogous devices.[4] Photoluminescence has served as an important technique for the measurement of temperatures of hot carriers.[5–7] It has now been used to study both steady-state distributions[8,9] and the picosecond time development[10,11] of temperature in several 2D systems.

In the experiments reported here, we have measured the steady-state photoluminescence spectra of modulation-doped quantum wells in which the 2D electrons (and holes) are heated well above the lattice temperature. We find that the carrier distribution can be described by a single temperature, even for electrons with an energy well above that of the polar-optical phonon. This result indicates that electron-electron scattering is faster than LO-phonon emission. In some of these experiments the optical excitation not only generates the luminescence, but also heats the electrons[5] since the photons have an energy, $h\nu_L$, greater than the band gap. We compare these results with experiments on the same samples in which weak optical excitation is used and the electrons are Ohmically heated. We find that the two methods of heating the electrons are equivalent only if we assume that all of the excess energy of the optically excited carriers is deposited into the electron system. This result shows that the energetic carriers thermalize through electron-electron scattering on a time scale which is too fast for significant LO-phonon emission.

The samples, named A (B), used in these experiments were GaAs-AlGaAs multi-quantum-well structures grown by molecular-beam epitaxy. They consist of fifteen GaAs quantum wells of width 137 Å (150 Å), separated by Si-modulation-doped $Al_xGa_{1-x}As$ barriers with $x=0.31$ (0.28) and width 242 Å (246 Å). The calculated electron areal density in each well (n_s) for sample A was 2.4×10^{11} cm^{-2}. For sample B Shubnikov–de Haas measurements give $n_s=2.5\times10^{11}$ cm^{-2} both in the dark and under illumination.

Spectra were taken with the samples cooled to low temperatures, immersed either in liquid helium or in a flowing He-gas cryostat. An incident laser wavelength of 676.4 nm was chosen so that it was not absorbed in the AlGaAs barriers and the light penetrated easily through all fifteen quantum wells. The incident laser intensity was kept low enough that the lattice temperature did not rise significantly, and the density of photogenerated carriers was no more than a few percent of the doped-in density.

A typical photoluminescence spectrum for a modulation-doped quantum-well sample is shown in Fig. 1. There we plot the logarithm of the intensity versus the energy of the emitted photon for sample A. The luminescence "turns on" at E_g, which is the band gap of the GaAs quantum wells modified by the confinement energy as well as the exchange and correlation energy of the 2D electrons. For photon energies $h\nu > E_g + E_F$ ($E_F \sim 9$ meV) $\log I$ drops linearly with increasing energy. Previous investigators have shown that the temperature, T_e, of the thermalized carriers

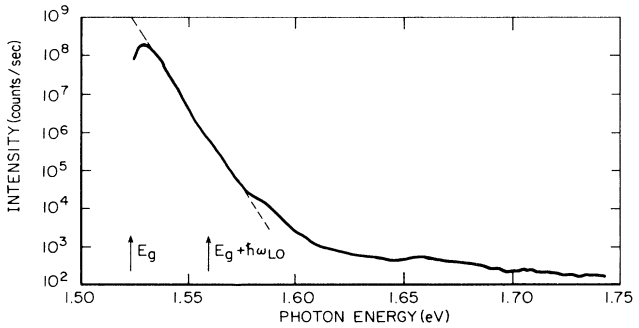

FIG. 1. Photoluminescence spectrum of sample A in a semilogarithmic plot showing exponential behavior over three decades, corresponding to an electron temperature of 58 K, with no structure at the threshold for LO-phonon emission at 1.56 eV. The bumps at 1.59 and 1.66 eV are evidence of recombination from higher subbands. The lattice temperature was 5.0 K.

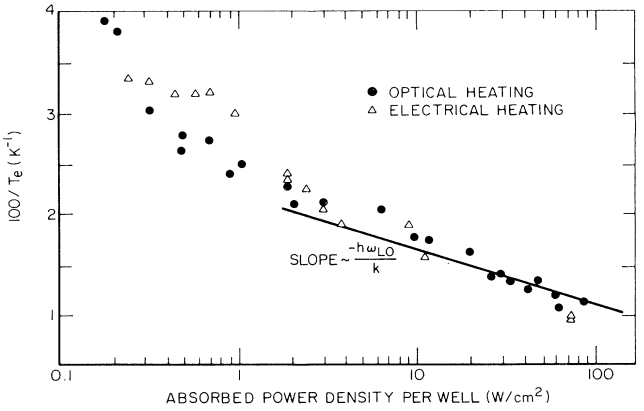

FIG. 2. Inverse temperature as a function of excitation intensity for sample B. For temperatures above 40 K, the LO-phonon emission dictates a straight line on the semilogarithmic plot with slope as shown: The position of the line is analyzed to yield the phonon emission rate.

(in equilibrium with one another, but not necessarily with the lattice) can be obtained from the slope of this portion (1.53 to 1.57 eV) of the luminescence spectrum.[5,7] The structures seen at 1.59 and 1.66 eV are due to luminescence processes involving electrons and holes in higher subbands. It can be seen in Fig. 1 that there is a considerable intensity at photon energies well above those emitted by the thermalized distribution. This luminescence has been attributed largely to geminate recombination of very hot carriers as they relax toward the band edges.[12]

It is interesting that the electron distribution can be characterized by a single temperature, T_e. As noted by Hess,[13] rapid LO-phonon scattering (the dominant energy-loss process for carrier temperatures above 40–50 K) should tend to deplete the distribution of carriers with kinetic energies larger than that of the phonon ($\hbar\omega_{LO}=36.6$ meV). The electron-electron scattering, on the other hand, attempts to maintain an equilibrium distribution described simply by an electron temperature. Thus the phonons tend to cut off the high-energy part of the Boltzmann tail, while electron-electron scattering repopulates it.

Figure 1 answers the question as to which is the dominant effect. It can be seen that the high-energy portion of the spectrum is fitted by a straight line even at energies well above $E_g+\hbar\omega_{LO}$. Shah *et al.* have made a similar observation.[9] This implies that the whole electron distribution is well described by a single temperature. The fact that no reduction in the tail can be observed means that electron-electron scattering is apparently much more rapid than LO-phonon emission in this sample. It would be necessary to use structures with considerably lower carrier densities for phonon scattering to dominate.

We turn now to discuss the dependence of T_e on the energy deposition rate (whether this occurs optically or electrically). From it we can determine the rate of electron cooling. By first comparing optical with electrical heating, we can further determine the efficiency by which excess optical energy is converted to electronic thermal energy. Figure 2 shows $100/T_e$ plotted versus deposited power density, for both optical and electrical heating. To determine electrical power input, we have measured the current through and the voltage across the sample using four-probe Hall-bridge contacts.[8] We have assumed that the total excess energy, $h\nu_L-E_g$ (where ν_L is the incident optical frequency), is converted into electronic thermal energy in obtaining the optical power input. The fact that the two sets of data points coincide (within noise fluctuations) verifies this assumption. This implies once again that electron-electron interactions are fast: Very little of the excess energy is lost by phonon emission on the time scale of electron-electron collisions.

The eventual importance of phonon emission is demonstrated in Fig. 2. At high temperatures, $T_e \gtrsim 40$ K, we expect on theoretical grounds that energy flow from the electronic system will be primarily through LO-phonon emission. Since we have shown that the carriers have a simple Fermi distribution even above $\hbar\omega_{LO}$, the power emitted per electron (at temperature T_e) can be written as

$$P(T_e)=(\hbar\omega_{LO}/\tau_{avg})\exp(-\hbar\omega_{LO}/kT_e). \quad (1)$$

In steady state, we can equate $P(T_e)$ with the heating power per electron, so that a plot of $1/T_e$ vs $\ln P$ gives a straight line with slope $\hbar\omega_{LO}$. This verifies LO-phonon emission (generated) as the principal energy-loss mechanism, for $T_e \gtrsim 40$ K. Below this temperature,

too few electrons have enough energy to generate an LO phonon, and so cooling is left to the less energetic and more weakly interacting acoustic phonons.

Finally, from the position of the linear data in Fig. 2, we can extract a value of $\tau_{avg} = 0.15$ psec. This measured phonon emission time is very close to that expected for a 150-Å quantum well. Using calculations by Price[14] and Ridley,[15] one obtains $\tau_{avg} \simeq 0.16$ psec. We have also calculated the effect of screening on the phonon emission rate, and find that it is negligible for the carrier density and temperatures in these experiments.[16] Screening becomes important for larger electron densities.

Recently other quasi-cw[9,17] and time-resolved[10] luminescence measurements have been reported in which the electron–LO-phonon coupling in quantum wells has been investigated. A phonon emission time of ~ 7 psec, more than an order of magnitude longer than our result, was needed to fit the time-resolved luminescence measurements. The origin of this discrepancy is not clear. In the high-power pulse experiments, screening by photogenerated pairs should be important, but it should be negligible both for the low-power pulse experiments and for ours. However, no change in phonon emission time with pulse power was found.[10]

The electron cooling that we observe is also about 10 times more rapid than that seen by Shah *et al.*[17] in similar experiments. The carrier densities in the samples used in their experiments are larger than ours, but the difference in screening is too small to account for an order-of-magnitude reduction in phonon emission. It is quite possible that hot-phonon effects, while not important in our experiments, will explain our disagreement with other determinations of τ_{avg}. The importance of phonon reabsorption is determined by the phonon lifetime, which may well be sample dependent.

In summary, our experiments have verified that hot 2D electrons ($T_e > 40$ K) cool by emission of LO phonons. We find that this process occurs at the rate predicted theoretically ($\tau = 0.16$ psec), but faster than several other measurements for similar systems ($\tau = 1.2$–7 psec). Our work does show conclusively that electron-electron scattering (at areal densities $\sim 2.5 \times 10^{11}$ cm^{-2}) is faster than electron-phonon scattering. This is evident from the fact that a single temperature characterizes the luminescence tails, as well as from our comparison with results from both electrical and optical heating, from which we conclude that virtually all excess electron-hole-pair kinetic energy is efficiently thermalized without phonon emission.

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