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60 mm. As initial beam radius we take the crossover size of about 50 μm. Substituting these values we find $R_M = 48\,\mu$m, which is of the same order of magnitude as the crossover size itself. First-order perturbation theory may be used in this case only to obtain an estimate of R_M, as Eq. (6) yields $28 < 50$ and Eq. (7) yields $1300 < 3000$.

Such a projection gun is thus severely limited in its performance by this effect. One can improve the gun by giving the beam a more homogeneous space-charge density distribution, for instance by the application of the so-called selective prefocusing lens.[3] The introduction of an unipotential lens to decrease the perveance of the beam may also improve the gun.

A parabolic space-charge density distribution acts in a diverging beam as a negative lens with third-order positive spherical aberration. Approximately, the increase of the virtual minimum cross section caused by the aberration is proportional to the perveance of the beam, the distance covered by the beam, and inversely proportional to the aperture angle [Eq. (14)]. This effect can severely limit the performance of high-brightness electrostatic projection TV guns.

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Photoluminescence from GaAs quantum wells under high electric fields

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The room-temperature photoluminescence spectra of n-modulation doped GaAs–AlGaAs multiple quantum wells have been studied at high parallel electric fields in order to obtain the distribution function of the two-dimensional electron system under high field conditions. The spectra show thermalized energy distributions with electron temperatures of ~ 600 K in the range where current instabilities indicate negative differential conductivity. This temperature is well below the value expected for bulk GaAs, and can be understood on the basis of real-space transfer of hot electrons into AlGaAs.

Two-dimensional electrons confined in GaAs by the conduction band offset to AlGaAs form the conducting channel of a whole new class of present and future high-speed devices,[1] such as the SDHT (selectively doped heterostructure transistor, also called HEMT, MODFET, and TEGFET), the various kinds of hot-electron transistors,[2] and devices based on the concept of velocity modulation.[3] In these devices high electric fields in the plane of the semiconductor layers are present causing carrier heating[4] and, consequently, transport effects related to the hot carrier distribution functions. The hot-electron transport effects in bulk GaAs are well understood on the basis of valley transfer into the satellite valleys in the conduction band. Theoretical works[5] indicate that electron temperatures of about 1000 K are necessary to cause negative differential conductivity due to valley transfer. In two-dimensionally confined electron systems, carrier heating may cause additional transfer effects into the confining barrier layers (e.g., AlGaAs), areas of different mobility. These effects, theoretically and experimentally studied by Hess and co-workers,[6] are summarized under the name "real-space transfer."

In this work we applied high fields parallel to the layers of n-modulation-doped quantum wells. We studied the photoluminescence spectra as a function of the applied voltage up to the point where the current saturates and current instabilities indicate negative differential conductivity (NDC). The distribution function as obtained from the spectra is a thermalized distribution function with electron temperatures of about 600 K in the range where the current instabilities begin. This value is well below the temperatures calculated for bulk GaAs to cause NDC by valley transfer of hot carriers. This is reasonable if real-space transfer is assumed to be the main effect causing the negative differential conductivity.

In our experiments n-modulation-doped multiple quantum wells, grown by molecular-beam epitaxy, were used. The samples consisted of the following layers: A quantum well of 109-Å GaAs, a "spacer" layer (42-Å AlGaAs, 11-Å GaAs, 42-Å AlGaAs, 11-Å GaAs), 210-Å AlGaAs (doped with Si, $n = 2 \times 10^{17}$ cm^{-3}), and a symmetric spacer layer. This structure is repeated 20 times upon a 0.5-μm buffer layer of GaAs on a Cr-doped semi-insulating substrate. The modulation-doping results in an electron concentration in the GaAs quantum wells of 7.3×10^{11} cm^{-2} per layer at room temperature, with a mobility of 7400 cm^2/V s. The Al concentration of all $Al_xGa_{1-x}As$ layers is $x = 0.33$. Ohmic n-type contacts were made by evaporating Au–Ge and alloying at 380 °C, followed by a second evaporation of Au. The

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contacts were defined photolithographically, leaving open distances of 50 μm. A mesa etch left an "active" area of $50 \times 50 \mu$m between the contacts. Within this area the field is assumed to be homogeneous. The sample is mounted as a part of a 50-Ω stripline circuit.

All measurements are done at room temperature. The electric field is pulsed at a repetition rate of 4 MHz with pulse durations of 10 ns, in synchronism with picosecond laser pulses (6-ps pulses, from a synchronously pumped mode-locked cavity-dumped dye laser, Rhodamin 6G, $\lambda = 606$ nm). The current in the circuit is measured by a sampling oscilloscope (Tektronix 7S11, 7T11, S-4). The laser pulses are focused on the area between the contacts, and typical photoexcited carrier densities are of the order of 10^{10} cm^{-2} per layer, thus much smaller than the electron concentration in the quantum wells. The resulting photoluminescence is collected into a 1/4-m single monochromator and a GaAs cathode photomultiplier. It was ascertained that the luminescence decays (due to recombination and carrier sweep-out) before the trailing edge of the electric field pulse. Thus, only luminescence during the presence of the electric field is detected. The setup is similar to previously reported experiments[7] made in p-type quantum wells, where the distribution of minority electrons in high electric fields was studied. The principle of the determination of the distribution function from the photoluminescence spectra is given in Ref. 8.

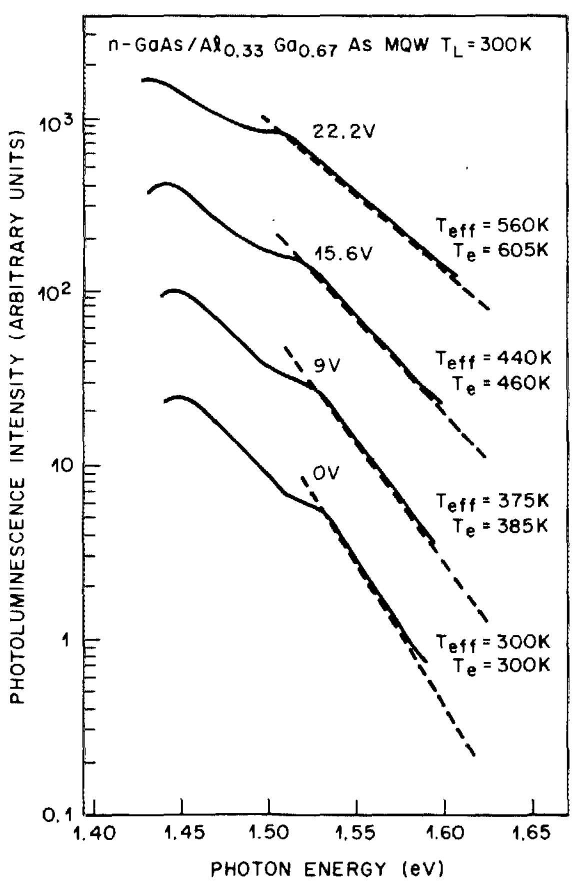

FIG. 1. Relative photoluminescence spectra for different applied voltages. The spectra are plotted on a logarithmic scale and have been vertically displaced for clarity.

The result of the experiments are the luminescence spectra at given applied voltages, with a simultaneous measurement of the current through the sample. Figure 1 shows the spectra for four different applied voltages. The spectra show a high energy tail that decreases exponentially with photon energy, in the range from 1.53 to 1.58 eV (the range where the spectra coincide with the dashed straight lines). We chose this range in order to characterize the distribution functions for the following reasons: On the low energy side the sensitivity of the photocathode decreases rapidly (below 1.45 eV). The shoulder around 1.52 eV represents the minimum of the second conduction subband[9] in the GaAs quantum well. Above this value the density of states of the two-dimensional electron system is constant over a relatively large range. Therefore the spectra in this range are a direct measure of the distribution function. With increasing applied voltage (increasing electric field) the slope of the exponential tail decreases, indicating the heating of the carriers.

The exponential tail in the spectra show that the carrier distribution functions can be described by thermalized distributions, characterized by carrier temperatures T_{eff}. This is not surprising, since at these high carrier densities (corresponding to $10^{18}\ \text{cm}^{-3}$) electron–electron scattering is effective enough[10] to cause a thermalized distribution function. For the quantitative interpretation of the spectra it is important to know the temperature of the holes, since the spectra are a product of both distribution functions. From the spectra we obtain an effective temperature T_{eff}, using

$$I(\hbar\omega) \propto \exp(-\hbar\omega/kT_{\text{eff}}) \; . \tag{1}$$

The electron temperature T_e is calculated from T_{eff} and the hole temperature T_h, using

$$T_e = [(m_e + m_h)/T_{\text{eff}} - m_e/T_h]^{-1} m_h \; , \tag{2}$$

where $I(\hbar\omega)$ is the spectral luminescence intensity, k is Boltzmann's constant, and m_e and m_h are the different effective masses (we use values of $m_e = 0.0665\, m_0$ and $m_h = 0.4\, m_0$). From a recent quantitative determination of the electron-hole energy transfer rate[11] we can estimate the hole temperature: In steady state the input power per hole from the electric field *plus* the energy transferred from the hot electron system by electron-hole Coulomb scattering (per unit time, per hole) must equal the energy loss from the holes to the lattice. The result of this balance equation, using the approaches as described in Ref. 11, shows that the hole temperature is closer to room temperature than to the temperature of the electrons. At the highest applied voltage, the hole temperature is approximately 390 K.

Figure 2(a) shows the results for the effective temperature and the electron temperature as a function of the applied voltage across the 50-μm length. In Fig. 2(b) the current as measured with the sampling oscilloscope is plotted: The current increases linearly at low voltages, then tends to saturate at a voltage of about 23 V. Above this voltage, current instabilities occur. These instabilities indicate negative differential conductivity, as expected for voltages beyond the voltage for maximum current (maximum drift velocity). On the sampling scope the signal has the shape schematically shown in the inset of Fig. 2. The applied voltage pulse (dashed line)

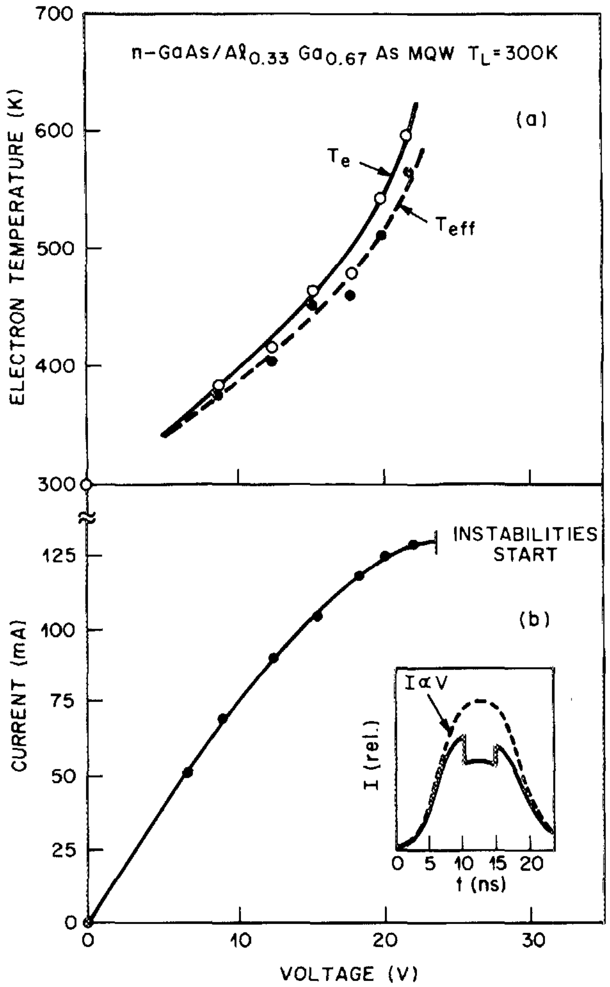

FIG. 2. Electron temperature and effective temperature as a function of the applied voltage (a) and current-voltage characteristics (b). The inset shows qualitatively the signal shape on the sampling oscilloscope in the region of negative differential conductivity.

causes an increasing current up to a value where the current rapidly drops (within less than 500 ps). This point represents the highest field where photoluminescence and current measurements can be correlated. At higher voltages, the field within the sample probably is not homogeneous due to domain formation as a result of negative differential conductivity. The electron temperature reaches a value of 600 K at the point where negative differential conductivity begins.

This represents the main result of our experiment: In the quantum well structure the electron temperature necessary to cause negative differential conductivity is much lower than expected in bulk GaAs. We interpret this as a result of the real-space transfer across the barriers to AlGaAs. The energy barrier (conduction-band offset) to $Al_xGa_{1-x}As$ at $x = 0.33$ is 0.27 eV (using a ratio of 60:40 of the conduction- and valence-band offsets), and the ground state in the quantum wells is about 40 meV above the conduction-band minimum. Therefore, real-space transfer at the observed carrier temperature of 600 K should be much more effective than valley transfer that causes NDC in the bulk at considerably higher carrier temperatures. This result is consistent with our results obtained for minority electrons in *p*-type quantum wells,[7] where similar electron temperatures have been shown to cause negative differential conductivity. At last, the question of *k*-space transfer *within* the GaAs quantum wells remains to be answered. The higher energy of the ground state in the Γ minimum of the conduction band should lead to valley transfer at lower carrier temperatures than in the bulk. The situation is furthermore complicated by the effects of confinement on the density of states in the GaAs X and L valleys. Quantitatively, however, the effect of valley transfer *within* the GaAs quantum wells is believed to be small compared to that of real-space transfer, due to the high density of states and effective volume in AlGaAs. We might add at this point that the electron temperatures under high field conditions in the bulk have never been directly measured in the range of NDC, where the valley transfer effects occur. Photoluminescence experiments under high field conditions have been performed by Takenaka *et al.*[12] at very low carrier densities and lower electric fields. Similar experiments in the range of NDC would be of great interest, also for a direct comparison of the results with our findings in quantum wells.

In conclusion, we have studied the photoluminescence spectra of GaAs/AlGaAs multiple quantum well structures at high electric fields. The thermal electron distribution functions can be characterized by temperatures of up to 600 K in the range where current instabilities due to negative differential conductivity are observed. This value—low as compared to that expected for the bulk NDC—is interpreted as being due to the real-space transfer of hot electrons into the AlGaAs.

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