

Electron-electron interaction in ballistic electron beams

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The transport of ballistic electrons emitted and detected by adjacent point contacts in a two-dimensional electron gas (2DEG) in the system GaAs/Al_xGa_{1-x}As was measured at 1.2 K as a function of the emitter current. Hot carriers with a surplus energy up to 15 meV above the Fermi level were generated by the current flow. It is shown that electron-electron scattering is the main limitation for the quasiparticle lifetime. The experimental data for the ballistic electron propagation from emitter to detector are explained without free parameters by a theory developed by Chaplik and by Giuliani and Quinn. In addition, it is shown that crossing ballistic electron beams in a 2DEG interact with one another, if one of the beams contains hot electrons in the zone of interaction. Experiments on the influence of impurities on the mean free path of ballistic electrons should be done with currents as low as 10 nA. Otherwise, the mean free path contains a contribution from electron-electron scattering. Electron-electron interaction of hot carriers is a serious basic limitation for future devices based on the transport of electrons in the mesoscopic transport regime.

I. INTRODUCTION

At low temperatures, below 4 K, electrons can propagate in two-dimensional electron gases (2DEG's) in an Al_xGa_{1-x}As-GaAs heterostructure over a few micrometers without suffering any collisions.¹ These ballistic electron beams can be generated and detected by means of quantum point contacts.^{2,3} The flow of ballistic electrons can be controlled from outside by potential barriers, reflectors, mirrors, by electrostatic lenses, and by local magnetic fields generated by miniaturized, superconducting loops.^{4,5} These control elements for the current flow are the basis for a possible new generation of electronic devices.

In this paper, it will be shown that for currents as low as 0.1 μA injected from a point contact, electron-electron interaction of the hot carriers is a very serious limitation for the controllability of ballistic electron beams. In a metal like, e.g., aluminum, current densities as high as 10⁶ A/cm², which occur in interconnections between individual transistors in an integrated circuit, will shift the Fermi surface only by 1.7 × 10⁻⁷ of its radius. In other words, hot electrons cannot be generated in metals by current flow. On the contrary, in a 2DEG in a semiconductor with its low electron density it is easy to increase the electron energy by current flow by as much as the Fermi energy, so that there is ample phase space available for electron-electron scattering.^{6,7} The most important inelastic scattering mechanism for hot electrons in a 2DEG are electron-hole pair excitations, plasma emission, and the excitation of LO phonons.⁷ LO phonons in GaAs are only excited when the surplus of energy of the hot electrons exceeds 36.8 meV. This limit will not be reached in the present investigation. There is also a threshold for plasmon emission. In the present case this limit is at 10.25 meV. It is exceeded only for

the hottest electrons investigated in this study.⁸ So we will confine ourselves in this paper mainly to that energy range of the hot carriers where electron-hole excitations are the main contribution to electron-electron scattering. Chaplik⁹ and Giuliani and Quinn⁷ have given the lifetime $\tau_{ee}(x)$ for an electron-hole pair in a 2DEG at $T = 0$ as

$$\frac{1}{\tau_{ee}(x)} = \frac{E_F}{4\pi\hbar} x^2 \left(\ln \frac{2q_{TF}}{k_F} + \frac{1}{2} - \ln x \right). \quad (1)$$

Here $x = \Delta/E_F$ is the fraction of surplus energy Δ of the electron relative to the Fermi energy E_F . q_{TF} is the Thomas-Fermi screening wave vector in 2D, given by $2m/(m_0\epsilon a_0)$ where ϵ is the dielectric constant and a_0 the Bohr radius. In GaAs $m/m_0 = 0.067$ and $\epsilon = 13.1$.¹⁰ Equation (1) is valid if $\Delta \ll E_F(2q_{TF}/k_F)$.

Spector *et al.*¹¹ have claimed that two beams of 2D ballistic electrons can penetrate each other with negligible mutual interaction. This result implies only a weak electron-electron interaction in the ballistic electron beam. On the other hand, Yacoby *et al.*¹² have clearly demonstrated that electron-electron interaction in a Young's double-slit interference experiment with ballistic electrons is the essential source for phase breaking. These authors were able to explain their data well with Eq. (1). Fasol¹³ and Fasol and Sakaki¹⁴ have extended the expression for the lifetime $\tau_{ee}(\Delta)$ [Eq. (1)] to finite temperatures and could even improve the description of the interference data by Yacoby *et al.* Molenkamp *et al.*¹⁵ have used focused ballistic electrons injected from an emitter into a collector point contact. They found that electron-electron scattering is the dominant factor determining the temperature dependence of the collimated beam. In the present investigation, we also use ballistic electrons, focused by a magnetic field from an emitter into an adjacent collector point contact. We were able to describe in an excellent way by means of Eq. (1) without

free parameters the reduction in emitter-collector transmission by electron-electron interaction of hot electrons and cool holes. In addition, we could show that interpenetrating ballistic electrons affect one another, in contrast to the observation made by Spector *et al.*¹¹

II. EXPERIMENT

The experiments were carried out using modulation-doped 2DEG's formed at the interface of GaAs and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$. The heterostructures were grown by molecular beam epitaxy (MBE) with a conventional Varian ModGen II system. The layer sequence consisted of 1 μm GaAs buffer, 40 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ spacer, 40 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ active channel doped to $2 \times 10^{18} \text{ cm}^{-3}$, and a 10 nm GaAs cap. The carrier concentration and mobility, measured at 1.2 K by the Hall effect and the Shubnikov-de Haas effect, were found to be $n = 2.2 \times 10^{11} \text{ cm}^{-2}$ and $\mu = 1.05 \times 10^6 \text{ cm}^2/\text{Vs}$. This corresponds to $k_F = 0.01176 \text{ \AA}^{-1}$, to $E_F = 7.85 \text{ meV}$, and to $v_F = 2.03 \times 10^7 \text{ cm/s}$. A schematic drawing of a first set of devices is presented in Fig. 1. Two adjacent point contacts, at a distance of 0.76 μm from one another, are formed by metallic gates (Cr/Au layers) on top of the heterostructure. The 2DEG is located 90 nm beneath the sample surface, i.e., by negatively biasing the gate contacts with respect to the 2DEG an emitter E and a collector C are formed. Electrons emitted by E are focused into the collector C by means of a magnetic field perpendicular to the 2DEG. Between the terminals 1 and 2 a current source generates an emitter current which was focused by a magnetic field into the collector. The voltage V_C generated by charging up the collector was detected between the terminals 3 and 4. The various Ohmic contacts were made with Ni-Ge-Au alloys. All measurements were done at 1.2 K. The gate voltage for the emitter point contact was chosen in such a way that only the last 1D subband contributed to the conduction. This corresponds to a quantized resistance of $h/2e^2 = 12.9 \text{ k}\Omega$. However, the resistance measured be-

tween the contacts 1 and 2 was found to be 16 k Ω . In other words, the kinetic energy of the injected electrons corresponds to 81% of the applied voltage. Similar conversion rates were observed by Laikhtman *et al.*¹⁶ and by Williamson *et al.*,¹⁷ who found values of 82% and 68%, respectively.

The electrons injected by a dc current through the last 1D subband have surplus energies Δ above the Fermi level ranging from 0 to Δ_m with Δ_m related to the dc emitter current I_{Em} by

$$I_{Em} = e \int_{E_F}^{E_F + \Delta_m} dE D_{1D}(E)v(E) = \frac{2e}{h} \Delta_m . \quad (2)$$

The energy dependencies of the 1D density of states D_{1D} and of the electron velocity v cancel each other, leading to conductance quantization.^{2,3} In the present experiment we have used an ac current $I_E = I_{Em} \sin 2\pi ft$ ($f = 13$ and 23 Hz) which generated a sinusoidal modulation of the surplus energy Δ with $0 \leq \Delta(t) \leq \Delta_m \sin 2\pi ft$ (Fig. 2). The modulation frequency f being only a few tens of hertz, the measurement is quasistatic. The modulation is used to improve the signal to noise ratio by using a lock-in technique. We have applied no additional dc voltage to the point contact. In the positive cycles of modulation the emitter ejects hot electrons whereas in negative ones cool holes are emitted. We have used peak currents up to 1200 nA, so that hot electrons up to 15.5 meV were ejected. This is about twice the Fermi energy for the present heterostructure. In a negative cycle of the modulation the value of the Fermi energy sets, of course, a limit to the coolness of the holes at $E_F - \Delta_m = 0$ (Fig. 2). In Fig. 3, there is shown the magnetic field dependence of the current I_C injected into the collector point contact by an emitter current with amplitude 28.3 nA which corresponds to a maximum of surplus energy of 0.37 meV or 4.6% of the Fermi energy. Figure 3 shows how the background was chosen for the determination of the collector voltage V_C . The collector resistance having been kept fixed at 4 k Ω , the collector current has been calculated by $I_C = V_C/4 \text{ k}\Omega$. The collector resistance

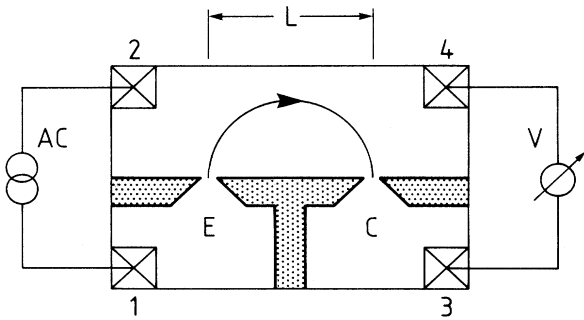


FIG. 1. Schematic drawing of an emitter point contact E and an adjacent collector point contact C formed by split gates. An ac current source is applied to the terminals 1 and 2. The collector voltage is measured between terminals 3 and 4.

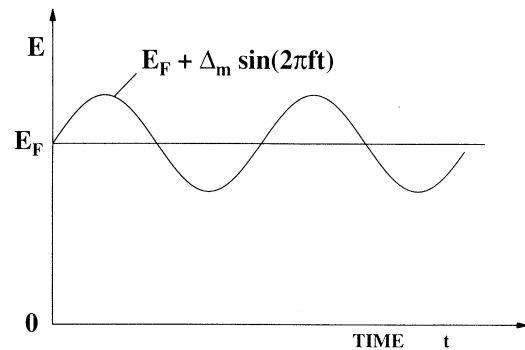


FIG. 2. Time dependence of the maximum surplus energy $\Delta(t) = \Delta_m \sin 2\pi ft$ in a sinusoidal modulation of the emitter current $I_E(t)$.

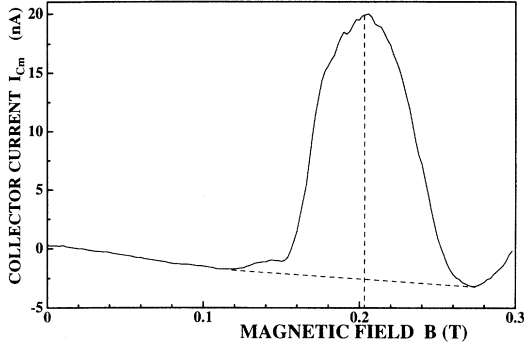


FIG. 3. Collector current I_C versus magnetic field B in a focusing experiment with emitter current $I_{Em} = 28.2$ nA. The maximum surplus energy Δ_m is only 4.6% of the Fermi energy. The dotted lines show how the background was subtracted for the determination of the collector voltage.

was adjusted to 4 k Ω by a resistance measurement previous to the focusing experiment. The emitter-collector distance L was deduced from the position B_0 of the first peak, according to $L = \Phi_0 k_F / \pi B_0$, where Φ_0 is the flux quantum 4.14×10^{-15} T m 2 . For the present sample, L turned out to be 0.76 μm .

III. ELECTRON-ELECTRON INTERACTION IN A BALLISTIC ELECTRON BEAM

We have measured the dependence of the detector current I_C as a function of the emitter current I_E (Fig. 4). For small emitter currents the detector current increases linearly $I_C = \alpha I_E$ with a slope $\alpha = 0.709$. The deviation of α from 1 is attributed to electron losses due to scattering at impurities. When the emitter current increases another loss mechanism becomes active, leading to a strongly reduced increase. This effect is better shown in Fig. 5, by displaying $I_{Cm} / \alpha I_{Em}$ versus I_{Em} . At the

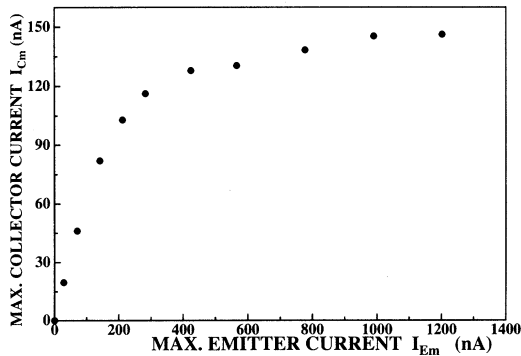


FIG. 4. Dependence of the maximum collector current I_{Cm} as a function of the maximum emitter current $I_{Em} = \sqrt{2}I_E$ for an emitter resistance $R_E = 16$ k Ω and a collector resistance of $R_C = 4$ k Ω . Only the last 1D channel is contributing to the conductance of the emitter. The E - C distance is $L = 0.76$ μm .

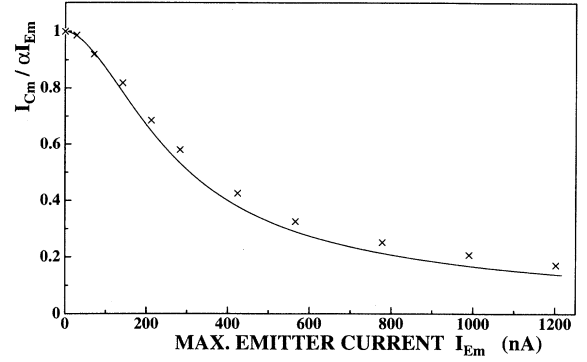


FIG. 5. Dependence of the current ratio $I_{Cm} / \alpha I_{Em}$ on $I_{Em} = \sqrt{2}I_E$ for the data from Fig. 4 (crosses). The full line gives the result of the simulation for sinusoidal excitation using $x = (1.644 / \mu\text{A}) I_{Em}$.

maximum emitter current of $I_{Em} = 1200$ nA an additional 83% of the current is lost at the collector by this second loss mechanism. We will now show that electron-electron scattering can account for the losses observed here.

If all the electrons in the ballistic beam have the same energy Δ_m , the losses due to electron-electron scattering on the half circle $\pi L / 2$ connecting emitter and collector are described by

$$H(x) = \exp \left\{ -\pi L / [2v_F \sqrt{1+x} \tau_{ee}(x)] \right\} \quad (3)$$

with $x = \Delta_m / E_F$ and τ_{ee} given by Eq. (1). $v_F \sqrt{1+x}$ is the velocity of the hot ballistic electrons. In Eq. (3) it is assumed that all electrons are emitted perpendicularly to the contact. For the present emitter this assumption is adequate since the emitter ejects the electrons in a fan with an opening smaller than $\pm 15^\circ$ as determined by additional experiments with opposite point contacts.^{5,1} Here the angular distribution of the emitted ballistic electron beam out of the point contact was determined by sweeping a small magnetic field to deflect the electrons into the opposite point contact. Furthermore, it is assumed in Eq. (3) that an electron no longer reaches the collector, once it has been scattered. This assumption was confirmed experimentally by Molenkamp *et al.*¹⁵ The relationship $H(x)$ is shown in Fig. 6 for $L = 0.76$ μm and a 2DEG with the properties as mentioned above ($n = 2.2 \times 10^{11}$ cm $^{-2}$). It turns out that the measured data in Fig. 5 cannot be described by Eq. (3), which holds for monoenergetic electrons. $H(x)$ decays much faster with x than the experimental data. In the present experiment the hot electrons are not monoenergetic. They rather have an energy distribution $g(u)$ which for a sinusoidal modulation has the form ($u = \Delta / E_F$ and $x = \Delta_m / E_F$)

$$g(u) = \begin{cases} \frac{1}{2x} \left(\frac{\pi}{2} - \arcsin \frac{|u|}{x} \right), & |u| \leq x, \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

The transmission function now reads

$$G(x) = \int_{-\bar{x}}^x du g(u) \exp \left\{ -\pi L / [2v_F \sqrt{1+u} \tau_{ee}(|u|)] \right\}. \quad (5)$$

The lower limit of integration $-\bar{x}$ is $-x$ when $x \leq 1$ and -1 when $x > 1$. We have evaluated the integral in Eq. (5) numerically. The exponent in the integral can be written as $\exp[-Au^2(C - \ln|u|)/\sqrt{1+u}]$. For the present sample ($k_F = 0.1176 \text{ nm}^{-1}$, $q_{TF} = 0.1934 \text{ nm}^{-1}$, and $L = 0.76 \text{ }\mu\text{m}$) the constants have the values $A = 5.5919$ and $C = 1.6909$. The transmission function $G(x)$ decreases much more slowly with x than the function $H(x)$ for monoenergetic hot electrons (Fig. 6). This is due to the fact that in $G(x)$ the less hot electrons in $g(u)$ are scattered less by electron-electron interaction. A comparison of the curves $H(x)$ and $G(x)$ shows that for the present 2DEG and for the present distance L between emitter and collector only the electrons with $u < 0.5$ have a chance to reach the detector. Also shown in Fig. 6 is the transmission function $F(x)$ for a dc current through the point contact with a constant distribution function $g(u)$:

$$F(x) = \frac{1}{x} \int_0^x du \exp[-\pi L / v_F \sqrt{1+u} \tau_{ee}(u)]. \quad (6)$$

As expected $F(x)$ decays faster than $G(x)$ but much less fast than $H(x)$.

For a comparison between the theory and the experimentally obtained values it must be taken into account that using a lock-in technique only the first harmonic of the collector signal is detected. Since the initial sinusoidal excitation current is distorted by the energy dependent scattering process, the actually measured collector signal differs slightly from the transmission function

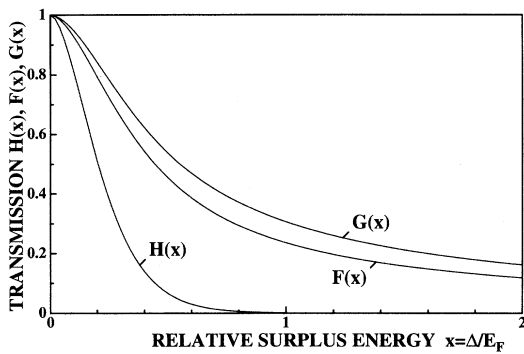


FIG. 6. Transmission function $H(x)$ of monoenergetic hot electrons versus the surplus of energy Δ_m relative to the Fermi energy E_F ($x \equiv \Delta_m/E_F$). The emitter-collector distance is $L = 0.76 \text{ }\mu\text{m}$. The Fermi momentum corresponds to an electron density of $2.2 \times 10^{11} \text{ cm}^{-2}$. $F(x)$ is the corresponding transmission function for hot electrons in a dc emitter current $I_{Em} = 0.6083x \text{ }\mu\text{A}$. For a sinusoidally modulated emitter current the corresponding transmission function is given by $G(x)$. Only the least hot electrons (and holes) in a beam reach the collector.

$G(x)$. Using a sinusoidal excitation current similar to $G(x)$, the first harmonic of the collector signal was calculated numerically. The result of this simulation is plotted in Fig. 5. Here, the following relationship between x and I_{Em} was used:

$$x \equiv \Delta_m/E_F = (12.9/7.85 \text{ }\mu\text{A}) I_{Em} = (1.644/\mu\text{A}) I_{Em}. \quad (7)$$

In view of the fact that the theory contains no free parameters the agreement between theory and experiment is very good. Although the experimental values are slightly larger than the calculated curve it can be concluded that the electron-electron scattering is the dominant scattering mechanism for hot ballistic electrons.

A few remarks must be made concerning the model presented here.

(i) Equation (1) for the electron-hole lifetime is valid only at $T = 0$ and for $\Delta_m \ll E_F(2q_{TF}/k_F)$. All measurements were done at 1.2 K, a temperature at which $k_B T$ is only 1.3% of E_F . The largest value Δ_m was 15.5 meV, compared to 25.8 meV for $E_F(2q_{TF}/k_F)$. Therefore Eq. (1) should be reasonably well applicable to the present experiment.

(ii) In the present model, hot electrons and cool holes, emitted in the positive and negative branches of a modulation cycle, are treated on an equal basis. That is why $g(u)$ and $\tau_{ee}(u)$ contain the modulus of u in Eqs. (4) and (5). Since it makes no sense to speak about cool holes with $x < -1$, there is a cutoff at -1 in the lower limit of integration in Eq. (5) as well as in the simulation shown in Fig. 5. Another source of asymmetry is found in the energy dependent velocity of the carriers, $v_F \sqrt{1+u}$. However, these features of the model play only a marginal role, since electrons and holes with $|u| > 0.5$ have in any case no chance to reach the detector, as shown by $H(x)$ in Fig. 6.

(iii) A monoenergetic beam of ballistic electrons with surplus energy $\Delta = uE_F$ will generate a first focusing peak in the detector at a magnetic field of

$$B_0 = \Phi_0 k_F \sqrt{1+u} / \pi L. \quad (8)$$

The peak will be broadened by the finite width of the angular distribution in the emitter and by the finite width of the emitter and collector openings. This broadening can be extracted from Fig. 3. The focusing peak has full width at half maximum of 0.069 T. In the present case we have a distribution of surplus energies between $+\Delta_m$ and $-\Delta_m$, rather than a monoenergetic beam. This generates an additional broadening of the focusing peak given by

$$K(B; x) = \int_{-\bar{x}}^x du \frac{1}{2x} \left(\frac{\pi}{2} - \arcsin \frac{|u|}{x} \right) \times \exp \left[-A \frac{u^2}{\sqrt{1+u}} (C - \ln|u|) \right] \times \delta(u - (B/B_0)^2 + 1) \quad (9)$$

with $B_0 = \Phi_0 k_F / \pi L = 0.2036 \text{ T}$. By numerically evaluating this function we have obtained the full width at

half maximum (FWHM) for the focusing peaks as a function of x (for vertical emission from the emitter and for emitter and collector with negligible opening). The FWHM increases linearly with x and saturates at 0.034 T. It leads to a broadening of the focusing peaks not larger than $\sqrt{(0.069)^2 + (0.034)^2}$ T = 0.077 T. This upper limit agrees reasonably well with the experimental value of 0.070 ± 0.006 T, which turned out to be independent of the emitter current within the accuracy of the data. It can be concluded that even if theoretically the hot electrons produce an additional broadening this effect is negligible in comparison to other broadening mechanisms. The small calculated additional broadening and the independence of the experimental values of the emitter current show again that only low energy electrons are able to reach the detector.

(iv) Kouwenhoven *et al.*¹⁸ have observed a pronounced nonlinear behavior of the point contact conductance as a function of the applied voltage. When the voltage exceeds the subband separation (3.5 meV in their case) the number of contributing 1D subbands is different for the two velocity directions, resulting in a strongly nonlinear current-voltage characteristic. We have observed no similar behavior although the voltage certainly exceeded 3.5 meV. The reason that we did not observe such a nonlinear behavior is probably again the strong suppression of the transmission for hot electrons, exceeding $u \approx 0.5$.

IV. ELECTRON-ELECTRON INTERACTION IN CROSSING BALLISTIC ELECTRON BEAMS

In this section we would like to address the question if a ballistic electron beam crossing the path of another ballistic beam further reduces the transmission of that beam, in addition to the effect of electron-electron scattering in the beam itself, as considered in the previous section. Spector *et al.*¹¹ have found no interference and argued that ballistic electron beams can be controlled in ways analogous to the manipulation of photons in linear optical systems. We could not confirm this conclusion and have found strong interference between hot ballistic electron beams penetrating one another. The experimental setup is shown in Fig. 7. There are three

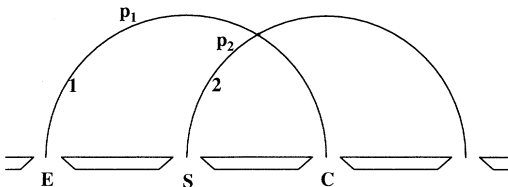


FIG. 7. Arrangement of three adjacent point contacts for testing the interaction of crossing ballistic electron beams. Electrons emitted in E (beam 1) are focused by a magnetic field into the collector C . A second emitter S emits another beam (beam 2) which crosses the path of the first beam in a zone of interaction. The distances from the emitters to the center of the zone of interaction are p_1 and p_2 .

quantum point contacts adjacent to one another at distances of $0.86 \mu\text{m}$ as determined by electron focusing. By means of a magnetic field perpendicular to the 2DEG (again GaAs/Al_{0.3}Ga_{0.7}As with the same parameters as in Sec. II) the electrons emitted from an emitter contact E are focused into a collector C . [$L(E-C) = 1.72 \mu\text{m}$.] As in the previous section a modulation technique without a dc bias was used. The modulation frequency was 21 Hz. A second emitter contact S emits another beam of ballistic electrons (with modulation frequency 273 Hz) which crosses the path of the first beam under an average angle of 60° . The center of interaction of the two beams is at $p_1 = \pi L/3 = 1.8 \mu\text{m}$ from the emitter E and at $p_2 = \pi L/6 = 0.9 \mu\text{m}$ from the emitter S . All three contacts had resistances of $8 \text{ k}\Omega$. The influence of the disturbance I_S on the collector signal V_C is shown in Fig. 8. The curves are similar to that of Fig. 4. The figure clearly demonstrates that with increasing I_{Sm} the ballistic beam from E to C is strongly reduced in intensity. Without crossing beam ($I_S = 0$) the current ratio $I_C/\alpha I_E$ could be analyzed as in Sec. III. The best fit of the experimental data, shown in Fig. 9, is obtained for $x = 0.725 I_{Em}/\mu\text{A}$. This relation corresponds to an emitter resistance of $5.7 \text{ k}\Omega$, which is 12% smaller than the quantized resistance $h/4e^2 = 6.45 \text{ k}\Omega$ for two conductance channels. We attribute the difference to the fact that at 1.2 K the point contact quantization is not well pronounced. Therefore it is difficult to accurately set the point contact conductance in the second to last plateau. The setting for the last plateau can be made much more accurately, as demonstrated in Sec. III. The influence of the crossing beam I_{Sm} is presented in Fig. 10 in another way. The ratio

$$\frac{V_C}{V_{C_0}} = \frac{V_C(I_{Sm}; I_{Em})}{V_C(I_{Sm} = 0; I_{Em})} \quad (10)$$

is plotted versus the disturbance with the emitter current I_{Em} as parameter. Two points are noteworthy. First, the losses due to electron-electron interaction in the beam

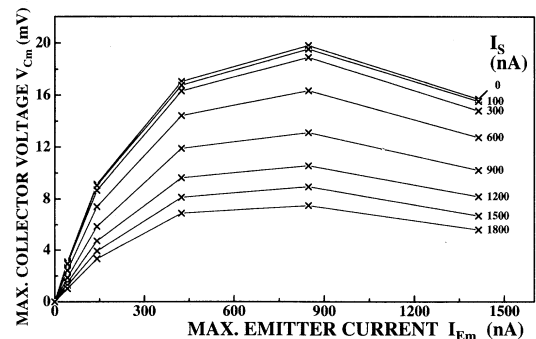


FIG. 8. Collector voltage V_C versus emitter current I_{Em} with the crossing beam 2 from Fig. 7 as parameter. The 2DEG has a density of $2.2 \times 10^{11} \text{ cm}^{-2}$. The distances $E-S$ and $S-C$ are $0.8859 \mu\text{m}$.

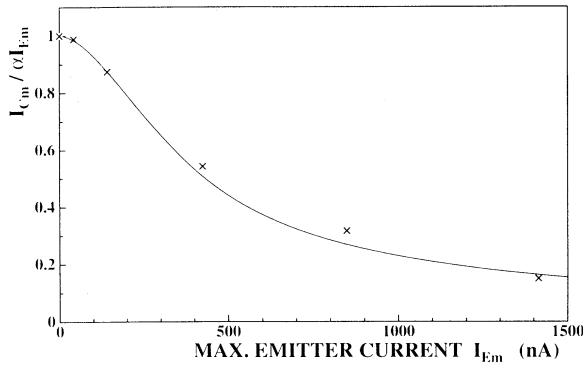


FIG. 9. Reduction of collector current I_C with increasing emitter current I_{Em} without crossing beam 2 in Fig. 7 (crosses). The fit of the data with Eq. (5) is shown as full line. $A = 12.621$, $C = 1.6909$, and $x = (0.725/\mu\text{A})I_{Em}$.

E - C are already subtracted in the plot. The decrease of V_C/V_{C_0} versus I_{Sm} is exclusively due to the interaction of the crossing beams. Secondly, the decrease in V_C/V_{C_0} is almost independent of the emitter current I_{Em} . We attribute this independence to the fact that the zone of interaction is $1.8 \mu\text{m}$ away from the emitter contact E . In Sec. III we have seen that after a path of $\pi L/2 = 1.2 \mu\text{m}$ all of the hot electrons have been scattered out of the beam. Here the path to the zone of interaction is even longer. Therefore it is not surprising that the energy spectrum of those electrons which reach the zone of interaction has become independent of the initial energy distribution.

The decrease of V_C/V_{C_0} in Fig. 10 can be understood qualitatively in a simple way. In the zone of interaction the electrons from the emitter E are not hot ($x \approx 0$), be it that they were not hot in E to start with (when I_{Em} is small) or that the hot ones were scattered out of the beam on the way from E to the zone of interaction. However, in the zone of interaction they become scattering partners for the hot electrons from the crossing beam S . By enabling the hot electrons to lose their surplus energy, they become scattered themselves out of the ballistic beam and no longer reach the collector C . This is the mechanism responsible for the decrease of V_C/V_{C_0} with increasing crossing current I_{Sm} , as shown in Fig. 10.

V. CONCLUSIONS

The results of the present investigation on the influence of electron-electron interaction on the propagation

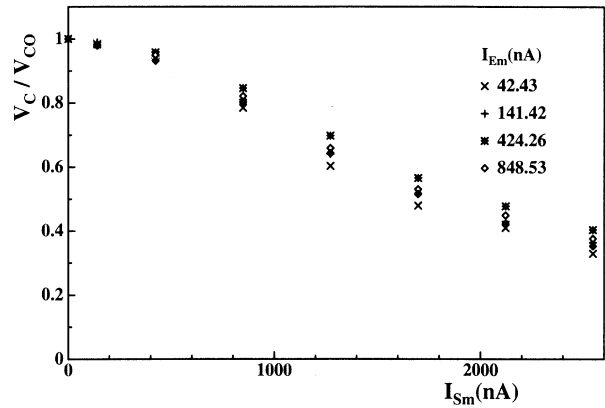


FIG. 10. Reduction of the collector signal V_C/V_{C_0} by a crossing electron beam with current amplitude I_{Sm} (see Fig. 7). The emitter current amplitude I_{Em} is the parameter.

of ballistic electron and hole beams can be summarized as follows.

(1) In a 2DEG at the interface of GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with hot carriers whose surplus energy is up to 15 meV above the Fermi level, the main contribution to the quasiparticle lifetime is electron-electron scattering. The lifetime is well described by a theory developed by Chaplik⁹ and Giuliani and Quinn.⁷

(2) Electron-electron interaction is a strong limiting factor for the propagation of hot electrons and cool holes. Currents as small as $0.1 \mu\text{A}$ emitted from a point contact with one 1D conductance channel are noticeably attenuated when they propagate over a distance of $1 \mu\text{m}$. Electron-electron interaction is a serious limitation for a possible new generation of electronic devices based on the propagation of ballistic electron beams in a 2DEG.

(3) Crossing ballistic electron beams in a 2DEG interact with one another, if one of the beams contains an appreciable fraction of hot electrons. This is in contrast to intersecting optical beams in a linear optical medium. The reason why Spector *et al.*¹¹ have not observed this interaction is the long distance the carriers had to propagate before they reached the area of interaction. When the beams no longer contain hot electrons in the zone of interaction the interference of the beams is negligible.

(4) Experiments for the determination of the mean free path of ballistic electrons limited by defect scattering should be done with currents as low as 10 nA. Otherwise, the mean free path contains a contribution from electron-electron scattering.

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