C^{sur} is the dopant surface concentration. The maximum defect supersaturation in the bulk ([P] = 0) is then given by

$$S = [\text{Defect}]^B/[\text{Defect}]^* = (1 + \alpha C^{sur})^2. \quad (9)$$

Since the tail enhancement is equal to this supersaturation, an order of magnitude of S is given by the experimental values of D_{tail}/D_i, i.e., $S \simeq 10$–15 at 1000 °C for C^{sur} in the range 2–3×10^{20} cm^{-3}.[14] Then (9) leads to $\alpha \simeq 10^{-20}$ cm^{-3} at 1000 °C, and from (7) using experimental values of D_i and D_{SD}

$$f/f_{SD} \simeq 3. \quad (10)$$

Since we are considering the majority defect for P diffusion, one must have $0.5 < f < 1$, and from (10)

$$0.16 < f_{SD} < 0.33, \quad (11)$$

i.e., $f_{SD} < 0.5$. Thus the majority defect for P diffusion plays the minor role for self-diffusion. Since it is now known that self-diffusion is governed primarily by the interstitialcy mechanism,[5] the diffusion of phosphorus takes place predominantly through a vacancy mechanism.

In conclusion, we can say that both experimental and simple theoretical evidences exist in favor of a major contribution of the vacancy assisted mechanism for phosphorus diffusion.

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Magnetic field dependence of hot-electron transport in GaAs

J. R. Hayes
Bell Communications Research, 600 Mountain Avenue, Murray Hill, New Jersey 07974

A. F. J. Levi and W. Wiegmann
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

(Received 14 June 1985; accepted for publication 20 August 1985)

We have studied the magnetic field dependence of hot-electron spectra using hot-electron spectroscopy. It is shown that application of a magnetic field normal to the injection direction has a dramatic effect on the spectra whereas a magnetic field applied parallel to the injection direction has no effect. The magnetic field is shown to increase the effective transit region width of the spectrometer enabling us to deduce a scattering rate for hot electrons that is at least four times greater than would be expected considering phonon emission alone.

Hot-electron transport is of both fundamental and technological importance. With ever decreasing device dimensions it is important to understand the behavior of hot electrons in small scale structures. Until recently, an understanding of hot-electron effects in semiconductors has been limited by a lack of experimental data with which to compare theoretical predictions. The introduction of a new spectroscopic technique—hot-electron spectroscopy—now enables one to obtain information on nonequilibrium carrier dynamics in semiconductors. The experimental method, described in detail in Ref. 1, uses the unique degree of control currently available with molecular beam epitaxy (MBE) to form two bulk triangular potential barriers in the conduction band of a single crystal of GaAs. In the structure described here we have incorporated two bulk triangular potential barriers separated by a region of n^+ (Si impurity) GaAs. The bulk triangular barriers were formed by placing a thin p^+ (Be impurity) layer in a region of low carrier concentration bounded by n^+ layers.[2] The grown epilayers were fabricated into a two-level mesa structure using standard chemical etching techniques to reveal the three n^+ layers. Ohmic contacts were made to the layers by rapidly thermally annealing an evaporated Au-Sn alloy.

A schematic cross section of the fabricated two-level mesa structure together with a diagram of the conduction-band edge is shown in Figs. 1(a) and 1(b), respectively. The voltages applied to, and the currents flowing in, this structure are best described using standard transistor notation where the emitter, base, and collector are indicated in Fig. 1.

In order to acquire a hot-electron spectrum the following procedure was adopted. With the transit region (base) at ground potential, a negative bias ($-V_{eb}$) was applied to the emitter so that a nearly monoenergetic beam of electrons was injected into the transit region. The emitter-base triangular

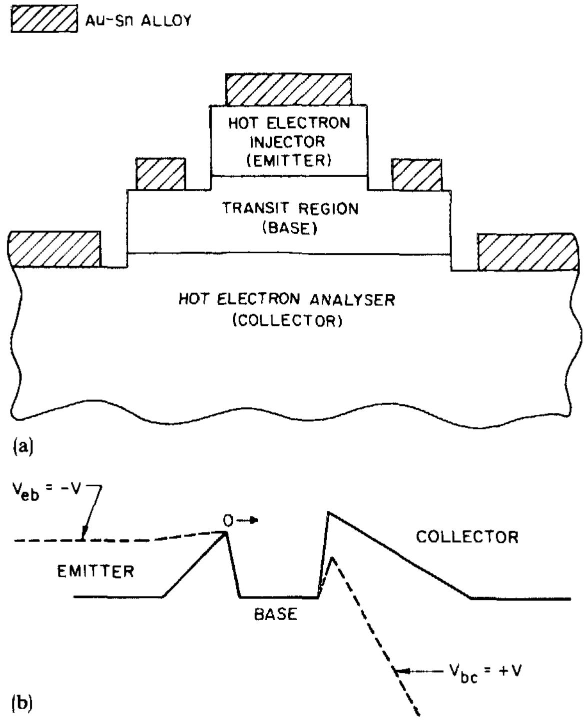

FIG. 1. Schematic diagram of the MBE grown GaAs epilayers comprising the two level mesa structure are shown in (a) together with a schematic of the conduction-band edge of the hot-electron injector (emitter), transit region (base), and hot-electron analyzer (collector) in (b). The broken lines indicate the conduction-band edge of the structure when biased.

potential barrier therefore formed the "hot-electron injector" injecting a narrow cone in the forward direction, normal to the plane of the barriers. The injected electrons were scattered in the transit region that had a carrier concentration of $1 \times 10^{18}\ \mathrm{cm}^{-3}$ and the resulting distribution at the far edge of the transit region was analyzed using the collector as a "hot-electron analyzer." The analyzer works by applying a positive bias V_{bc} to the collector with respect to the transit region. This has the effect of lowering the barrier energy ϕ_{bc}, enabling spectroscopic information on the electron distribution to be obtained. It was shown in Ref. 1 that

$$\frac{dj_c}{dV_{bc}} \propto n(p_n^0),$$

where j_c is the collected current, $n(p_n^0)$ is the distribution of hot-electron momentum normal to the plane of the triangular barriers, $p_n^0 = \sqrt{2m_e\phi_{bc}}$, and m_e is the effective electron mass. In this way, measuring dj_c/dV_{bc} as a function of the base/collector bias, one obtains detailed spectroscopic information on scattering mechanisms in the transit region. For moderate carrier concentrations ($\sim 1 \times 10^{18}\ \mathrm{cm}^{-3}$) the interaction of hot electrons with the coupled plasmon/phonon modes in the transit region is expected to dominate inelastic scattering events in GaAs.[3]

In this letter we describe the effects that a magnetic field, applied perpendicular to ($B_\perp$) and parallel with ($B_\parallel$) the direction of electron injection, has on hot-electron spectra. The study was undertaken for two reasons: firstly to measure changes in a given spectrum with applied magnetic field to establish that hot-electron effects were indeed being observed and secondly to infer a scattering rate for hot electrons from changes in the spectra with $B_\perp$.

The simplest description of hot-electron transport utilizes a classical kinematical model in which an electron injected into the transit region, prior to the application of a magnetic field, has a straight trajectory between scattering events. However, when a magnetic field is applied, this trajectory is modified, the electron describes part of a circular orbit between collisions, the radius of which (r) is given by

$$r = pc/B_\perp e,$$

where p is the electron momentum, e its charge, c the velocity of light, and $B_\perp$ the applied magnetic field.

To understand the effect of the magnetic field consider what would happen to an electron transiting from the injector to the analyzer without a collision, i.e., a ballistic electron. A hot electron injected into the transit region with energy ϕ_{eb} and with all its momentum, $p = \sqrt{2m_e\phi_{eb}}$, in the forward direction is analyzed after traversing d, the transit region width. When $B_\perp$ is applied to the sample, two effects occur that influence the collection of the injected electron. Firstly, the electron trajectory is increased from d to d', and hence the probability for an electron to be scattered is increased. Secondly, although the magnitude of the momentum of a ballistic electron remains unchanged, its normal component is reduced when it reaches the analyzer because of the imposed circular orbit. The analyzer barrier, discriminating only against the normal component of momentum, collects the electron at a lower barrier energy. This qualitative description of ballistic electron transport in a magnetic field may be applied in a natural way to the case of nonballistic, hot-electron transport. The application of $B_\parallel$ should show no change in the spectra since $B_\parallel$ has no effect on the normal component of momentum.

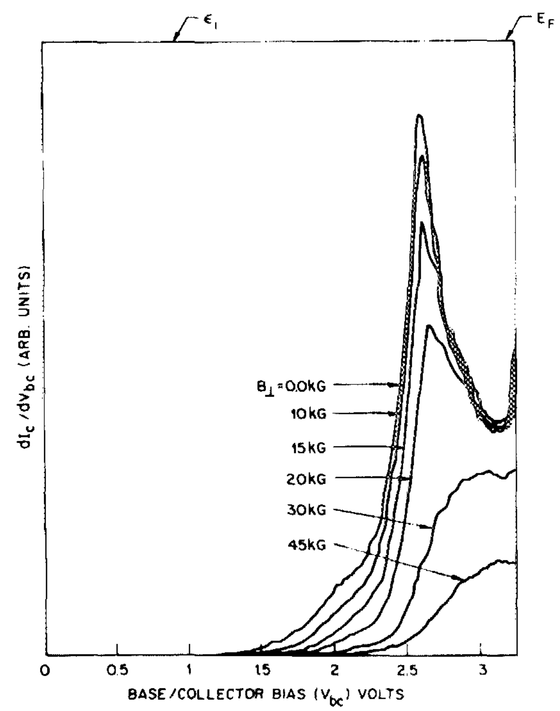

FIG. 2. Magnetic field dependence of a hot-electron spectrum when a magnetic field is applied perpendicular to the direction of current flow at the hot-electron injector (emitter). The injection energy ϵ_i and the position of the Fermi energy E_F are indicated for this particular sample having a transit region width of 1200 Å.

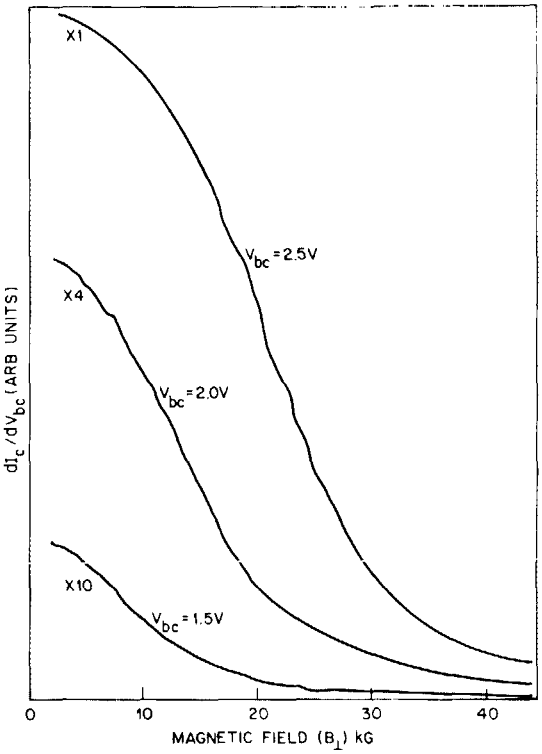

FIG. 3. Variation of spectral intensity with applied magnetic field for three indicated hot-electron analyzer (collector) biases.

The results of measurements at 4.2 K on a sample having a transit region width of 1200 Å and an injection energy of 0.25 eV above the Fermi energy are shown in Fig. 2 for $B_\perp$ up to 4.5×10^4 G. At these fields the application of $B_\parallel$ showed no change in the spectra. Because the transit region width is far greater than the average distance between scattering events (mean free path of a few hundred angstroms) few ballistic electrons are observed in the spectrum with $B_\perp = 0$ (seen in Fig. 2), i.e., there is no peak at the injection energy, ϵ_i. There are, however, two outstanding features of the spectrum which should be pointed out, the pronounced peak (at ~2.6 V bias) close to the Fermi energy and the shoulder at higher barrier energies (~2.0 V bias). We note that the ratio of emitter to collector current is 0.17 and 0.08 at voltage biases of 2.6 and 2.0 V, respectively. Upon application of a magnetic field both features are dramatically altered; the shoulder disappears and the peak merges with the Fermi energy at 4.5×10^4 G. For clarity the variation of the spectra with $B_\perp$ for three barrier energies (corresponding to 1.5, 2, and 2.5 V bias) is shown in Fig. 3. It is possible to infer a hot-electron scattering rate from the magnetic field dependence using two reasonable assumptions. Firstly, electrons scattered due to an increase in effective transit region width (d to d') lose sufficient energy that they no longer contribute to the collected current at a given analyzer energy. Secondly, the change in the average perpendicular momentum of electrons not scattered due to the increase in the transit region width is given by the cross product of the magnetic field and the velocity. Using these assumptions we have obtained a scattering rate for hot electrons of $2–3\times10^{13}$ s^{-1} from the variation of the spectra at an analyzer bias of 1.5 V (Fig. 3). This is at least four times the rate we would expect for phonon emission alone. Further, from the variation with B field of the high energy (less than 2.0 V bias) portion of the spectrum we are able to conclude that, for these hot electrons, $n(p)$ is peaked in the forward direction. Finally, it is interesting to note that application of a magnetic field of $B_\perp = 3\times10^4$ G on a sample of 1200 Å allows one to reproduce the spectra of a sample having a transit region width of 1700 Å with $B_\perp = 0$.

There are a number of complications to be considered if a more complete description of hot-electron magneto transport in the structure illustrated in Fig. 1 is to be given. Electrons injected from the emitter into the base gain kinetic energy from the rapidly varying potential between the top of the emitter barrier and the transit region. The electric field E in this short (~200 Å) acceleration region is large (~1×10^5 V/cm) and although there is expected to be little scattering of electrons in this region (because of the lack of mobile charge carriers) the effect of the application of a magnetic field must be considered. The equations describing the motion of an electron in crossed E and B fields are well known[4] and may be categorized according to the ratio E/B. If $E/B < 1$ the magnetic field dominates, there are oscillations in the motion and on average no acceleration in the electric field direction. If $E/B > 1$ the motion is essentially of the electric field type, there are no oscillations and on average there is acceleration in the electric field direction. In the experiment described here modest magnetic fields (of less than 5×10^4 G) were used so that the electron motion is determined by the strong electric field of the injector. A description of electron motion between the transit region and the top of the collector potential barrier depends on the bias applied to the collector. At low bias, when the E field is strong, the motion is determined by the E field whereas at high bias, when the E field is weak, the motion is of the B field type. In the experiments described in this letter the transit region width was large (~1200 Å); therefore, the motion of electrons in the transit region dominates the observed spectrum.

We believe that the application of the magnetic field has enabled us to draw a number of important conclusions. Firstly, the magnetic field dependence of the observed spectra is strong evidence that nondiffusive, hot-electron transport is being measured. Secondly, the hot electrons at high energy (less than 2.0 V bias) have a nonisotropic distribution with momentum peaked in the forward direction. Finally, the magnetic field shifts the spectra in a predictable way, enabling us to infer a scattering rate for hot electrons in GaAs.

We wish to thank S. J. Allen, S. L. McCall, and H. L. Störmer for useful discussions and T. Uchida for technical assistance.

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