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Quantum Interference Effects in GaAs/GaAlAs Bulk Potential Barriers

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We have observed ten oscillations in the current/voltage characteristic of GaAs/GaAlAs triangular potential barriers due to quantum interference effects. When an exact number of periods of a standing wave is present in the barrier there is a maximum in the transmission coefficient for electrons. As the bias is changed the electron wavelength is changed and there will once again be a maximum when the next complete period of the standing wave is incorporated. The observation of this quantum interference effect enables us to conclude that the scattering rate for hot electrons, high in the energy band of GaAs, is much less than previously assumed.

Recent technological advances in semiconductor epitaxial growth have enabled researchers to vary the band edges of many semiconductor alloys in a controlled fashion¹⁻³⁾. This has enabled one to directly observe non-equilibrium electron distributions $^{4-5)}$ using hot electron spectroscopy, allowing one to obtain the first experimental evidence for the existence of unscattered electrons (ballistic electrons) and electron activation from the Fermi sea.⁶⁾ In previous hot electron studies the triangular potential barriers had aspect ratios of 5:1 with the long arm being typically 150-200nm. In more recent experiments the triangular potential barrier has been narrowed (long arm of barrier is 85nm and the short arm 15nm) and by doing so we have observed a large number of oscillations in the current/voltage characteristic of the narrower triangular potential barriers.

A GaAs/GaAlAs structure, designed for hot electron spectroscopy studies, had two bulk triangular potential barriers grown back to back. The samples were grown by molecular beam epitaxy (MBE) on (100) semi-insulating GaAs substrates and comprised two bulk triangular potential barriers separated by a 100nm GaAs transit region doped n-type to 1x10¹⁸ cm⁻³. The hot electron analyzer at the base/collector junction was obtained by linearly compositionally grading from GaAs to AlGaAs (Al=25%) over 85nm and then back down to GaAs over a further 15nm. The second bulk triangular potential barrier at the base/emitter junction forming the hot electron injector was compositionally graded over the same dimensions as the hot electron analyzer but had a lower Al concentration of 20% at the peak. The epitaxial wafer was etched into a two level mesa structure and Ohmic contacts were made to the emitter, base and collector by rapidly annealing an evaporated Au-Sn alloy for lsec at 400°C. A schematic diagram of the conduction band edge forming the structure is shown in Fig. 1.

The current/voltage characteristic of the base/collector triangular potential



Fig. 1. Schematic diagram of the conduction band edge of the hot electron transistor formed from two compositionally graded GaAs/GaAlAs triangular potential barriers. The dashed lines represent the conduction band edge of the structure under bias.

barrier measured at 4.2K is shown in Fig. 2. It has almost ideal characteristics with some departure occurring at high current densities due to some voltage drop across



Fig. 2. The second derivative of the current voltage characteristic of the hot electron analyzer measured at 4.2K is shown by the solid line. The dashed line is the current/voltage characteristic obtained when a current of 100uA is injected into the transit region from the emitter.

the ohmic contact resistance. Close scrutiny of the current/voltage characteristics reveal a series of oscillations over the whole voltage range. In order to enhance the oscillation amplitude the second derivative of the current voltage characteristic has been taken and is plotted on an arbitrary logarithmic scale as a dotted line on Fig. 2. There are ten, clearly observable, oscillations which increase in period with increasing voltage bias; no similar structure is observed biasing the barrier in the opposite sense. Upon warming the sample the oscillation amplitude decreases being difficult to discern at temperatures greater than 55K.

By varying the emitter/base bias it is possible to show that the oscillations do not result from transport in the base but are a result of transport in the collector. We believe, and this will be discussed in detail later, that the oscillations arise from interference between incident and reflected electrons in the positive kinetic energy region of the analyzer barrier. Such oscillations were predicted by Gundlach () and a few periods have been seen in the I/V characteristics of M/I/S structures⁸⁾ and it has been proposed that these effects may have been observed in semiconductors $^{9)}$. However only two periods have been observed. In the M/I/M system the reflection occurs from both sides of the trapezoidal barrier whereas in our structure the oscillations occur because electrons can reflect from the top and bottom of the long arm of the hot electron analyzer triangular potential barrier.

When an electron enters the high field region of the graded barrier, if it is not scattered, its forward momentum increases dramatically serving to collimate the electron distribution, such that in our particular structure there is only a 1% difference in the path length independent of the injection angle; the injected electrons becoming better collimated at

higher biases. Hence, averaging over all incident electron directions around the Fermi Sea the ballistic electron distribution can be considered to be collimated in the direction of the electric field. Since the electric field is large it is reasonable to model transport in the long arm of the barrier by solving the one dimensional Schrodinger equation. For our particular barrier configuration, using standard GaAs parameters, we can calculate the transmission coefficients for electrons in the barrier region. The transmission coefficient, as pointed out by Gundlach () in such a region will have a series of oscillations. When a complete standing wave is incorporated in the barrier arm there will be a maximum in the transmission coefficient. With a further increase in bias there will be an decrease in the transmission coefficient and not until sufficient bias is applied, such that a further period of the standing wave is incorporated will another maximum exist, i.e. each successive oscillation in the current/voltage characteristic corresponds to the incorporation of a further period of a standing wave in the analyzer barrier. By subtracting a fifth order background current polynomial fit to the measured data we obtain a set of oscillations shown in Fig. 3. with amplitudes about 10% of the total current at a particular bias. The calculated oscillation period, with no adjustable parameters, leads to a set of oscillations which correspond closely to the measured period and are indicated as arrows on the upper horizontal axis of Fig. 3. The amplitude however depends on the exact potential and in particular the way the boundaries are terminated. It is clear to see why oscillations are not observed when the device is biased in the opposite sense since it is impossible to incorporate

a complete standing wave over such a small region.



Fig. 3. Amplitude of current/voltage characteristics (I_c) obtained by subtracting a fitted fifth order polynomial fit from the measured data. As can be seen the maximum oscillation amplitude is less than 15% of the current.

In order to confirm that these oscillations were due to such effects we measured the magnetic field dependence of the hot electron analyzer current/voltage characteristics. In particular we have applied a magnetic field both normal and perpendicular to the hot electron analyzer. When the magnetic field was applied parallel to the direction of electron injection there was no noticeable effect on the current/voltage characteristic, up to magnetic fields of 9T. Alternatively, a magnetic field applied normal to the direction of electron injection has a large effect. In Fig. 4 the oscillations, with background subtraction are shown as a function of bias for OT (solid line) and 5T (broken line). There is a dramatic change in the amplitude of the oscillations, particularly at low bias (<0.9Vhc) where they can no longer be seen. The small amplitude, larger oscillation period is a result of the polynomial fit and can be seen superimposed on the OT curve. The decrease and final disappearance of the oscillations is consistent with our model. When the magnetic field is applied the



Fig. 4. Oscillation amplitude measured at OT (solid line) and 5T (broken line).

motion must be described by transport in crossed electric and magnetic fields. The equation describing the amplitude of the oscillations may be characterized by the ratio of $m_{e}E/e^{2}B^{2}$, where m_{e} is the electron effective mass, e the electronic charge, E the electric field, and B the magnetic field, which describes the transition from electric field to magnetic field type in this structure. The disappearance of each oscillation is consistent with this model and yields a value of 0.09m, for the effective electron mass; which, considering the limited amount of band structure information included in the calculation, is quite remarkable. When this value is exceeded the electron motion is essentially of the magnetic field type having no net acceleration in the electric field region. Hence, increasing the magnetic field serves to remove oscillations of higher order that are in a higher electric field region.

These quantum interference effects can only exist if the electron wave function is coherent over the hot electron analyzer i.e. electrons have traversed the long arm of the hot electron analyzer without scattering. Calculations of the transmission coefficient indicate that the oscillation amplitude is relatively insensitive to the material parameters; although the absolute transmittance can be

strongly affected by temperature (velocity spread) and potential termination. Therefore, any change in the amplitude can be considered, to first order, to be due changes in the mean free path of the carriers in the region. The measured amplitude would indicate that the electron scattering rate decreases at high energies. In particular the scattering rate would have to be much less than the commonly accepted value of around $5 \times 10^{13} s^{-1}$ (a mean free path of about 20nm), at energies well above the threshold for intervalley scattering, to see oscillations. A lack of knowledge of the exact potential shape prevents us from obtaining an accurate number for the scattering rate of high energy electrons, but we conclude that it is around $5 \times 10^{12} \text{s}^{-1}$. The design of a better terminated potential barrier will lead to quantitative information.

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