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Hot Electron Transport in a Graded Band Gap Base Heterojunction Bipolar Transistor

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We report the direct observation of electron heating in an electric field using hot electron spectroscopy. The device structure used for the study was a graded band-gap base heterojunction bipolar transistor, fabricated in the GaAs/AlGaAs semiconductor alloy system. A thermal electron distribution at 4.2K was injected from the emitter into the base of the transistor that was compositionally graded to yield a quasi-electric field of $20kVcm^{-1}$. The equilibrium electron distribution was heated by the electric field and could be characterized at the end of the 90nm base region, by an effective electron temperature of 650K.

The incorporation of heterojunctions or doping charge sheets in electronic devices enables one to realize, intentionally or unintentionally, structures in which non-equilibrium charge carriers can play an important role. In order to understand the dynamic properties of emerging electronic devices it is essential to understand the transport properties of these charge carriers. The transport properties of non-equilibrium electrons, injected from a potential step has been characterized in degenerate n & p-type GaAs using hot electron spectroscopy.[1-3]

In addition to understanding the transport dynamics of hot electrons injected into a region of no electric field, the transport properties of charge carriers in the presence of an electric field is also of great interest. In particular the high electric field transport properties of minority carriers in heavily doped p-type semiconductors has received much attention since it was observed that the electron drift velocity saturates in p-type InGaAs[4], at fields many times greater than the threshold field for the Gunn effect. It was suggested that the absence of a negative differential resistance region in this case, was due to the strong interaction between the minority carrier electrons and the background holes. This effect has recently been modeled in GaAs[5] and InGaAs.[6] Both investigations found that when electron-hole scattering was included the transfer of electrons to the subsidiary minima was significantly suppressed, even at low hole concentrations. Similar experimental evidence for an enhanced scattering rate has also been obtained in silicon.[7] Recent calculations by Levi et al show that the energy loss rate for hot electrons in p-type material[8] is enhanced for electrons with energies in the 50-200meV range. Similar energy loss rates are obtained for n-type material.[2]

In this work we describe the first detailed investigation of the electron distribution resulting from interactions with a quasi-electric field obtained by compositionally grading AlGaAs. Levine et al[9] has studied the drift velocity in a compositionally graded region having a low quasi-electric field of $1.2kVcm^{-1}$ using reflectivity techniques and obtained a value of $2.3x10^{6}cms^{-1}$. In our experiments we are looking at transport in high electric fields ($20kVcm^{-1}$). In order to study the carrier transport in such a system we have realized hot electron spectroscopy in a graded band gap base transistor so that we can spectroscopically resolve the electron distribution after transit in the high electric field, compositionally graded region. The use of hot electron spectroscopy to address this problem allows determination of the entire electron distribution function rather than just an ensemble velocity.

We have chosen similar parameters for the design of the graded band-gap base transistor as those previously used to study the transport properties of electrons in a uniform base transistor. However, the graded base transistor differs in two important ways. Firstly a quasi-electric field of $20kVcm^{-1}$ exists in the base that is obtained by compositionally grading the Al content of $Al_xGa_{1-x}As$ in the base from x=0.15 to 0.0 over 90nm. Secondly electrons are injected into the base at thermal equilibrium (the previous transistor had a hot electron injector) and obtain a non-thermal distribution by gaining energy from the quasi-electric field.

The transistor structure was grown by molecular beam epitaxy (MBE) on a <100> semi-insulating GaAs substrate. A schematic diagram of the epitaxial layers is shown if Fig.1. The layers comprising the transistor consisted of a 600nm n^+ GaAs buffer layer followed by a $n=2x10^{17}cm^{-3}$ AlGaAs collector, with an Al fraction of 0.35 and compositionally graded over the 5nm closest to the base. The base was doped p-type with Be to $2x10^{18}cm^{-3}$ and graded over 90nm from GaAs, at the collector side, to AlGaAs (Al composition 0.15) at the emitter. This resulted in the base region having a quasi-electric field in the conduction band of $20kVcm^{-1}$. The electrons were injected into the base from an AlGaAs (Al composition 0.15) emitter doped n-type to $2x10^{17}cm^{-3}$ that was compositionally graded up to an Al composition of 0.2 over 13nm to remove the heterojunction spike in the conduction band enabling an equilibrium electron distribution to be injected into the compositionally graded base.[10] A final thin n^+ layer was grown to facilitate ohmic contact formation to the emitter. The structure was fabricated into a two level mesa structure using standard chemical etching techniques to reveal the emitter, base and collector for ohmic contact formation. Ohmic contacts were made by annealing a Au-Sn alloy to the emitter and collector and a Au-Be alloy to the base.

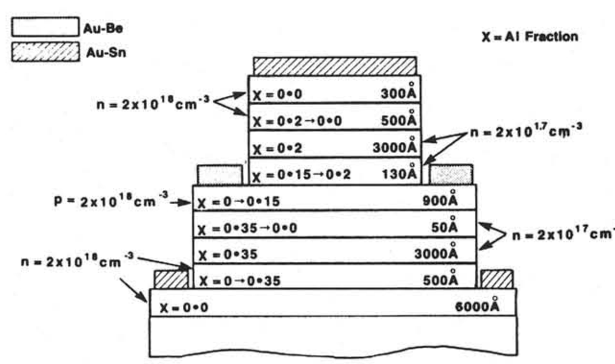

Fig.1 Schematic diagram of the epitaxial layers comprising the graded band-gap base bipolar transistor. The emitter had an area of $7.85x10^{-5}cm^{-2}$.

A schematic diagram of the energy band of the transistor is shown in Fig. 2. The transistor had a current gain of 330 at room temperature increasing to 1600 when cooled to liquid Helium temperatures where the hot electron measurements were made.

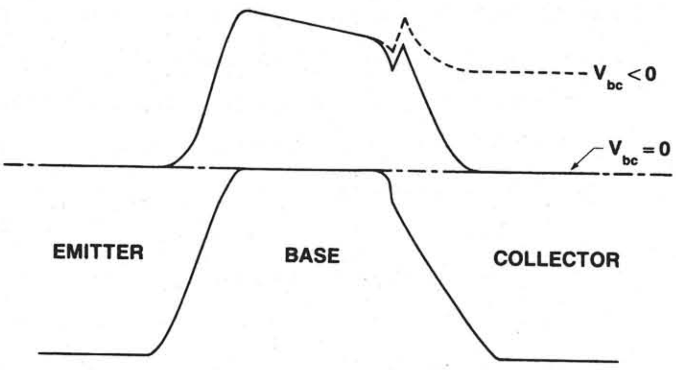

Fig.2 Schematic diagram of the graded band-gap base bipolar transistor used in this study. The solid line shows the band structure of the device in equilibrium and the dashed line indicates the band edge with a forward bias applied to the base collector junction.

The emitter was forward biased to inject an equilibrium distribution into the base region. The hot electron spectrum was obtained by forward biasing the collector with respect to the base. When the base/collector junction is forward biased the heterojunction barrier increases and at V_{bc}=0.4V begins to analyze the distribution that has traversed the base. The heterojunction barrier energy increases linearly with bias and finally injects a large number of electrons into the base. However, before this high injection condition is reached most of the electron distribution is analyzed. This is insured by having a larger Al composition (x=0.35) in the collector than the Al composition that exists at the emitter end of the base. When the electron distribution is fully analyzed the heterojunction barrier has been raised to about 0.23eV. The measured hot electron spectrum is shown in Fig. 3. for injection currents of 0.5 and 1mA. There is no significant difference in the spectra other than amplitude. The emitter current density is kept low <15Acm^{-2} so that the voltage drop across the base resistance will be minimal. In accordance with previous measurements[3)] we have analyzed the results in terms of an effective electron temperature and found that significant heating occurs such that the distribution can be characterized by an effective electron temperature of 650K.

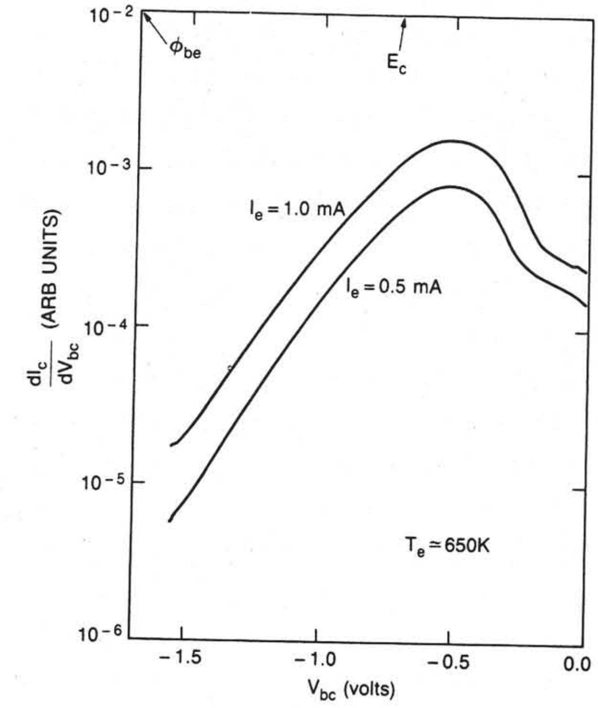

Fig.3 Measured hot electron spectra obtained for two indicated emitter injection levels. The position of the conduction band edge of the emitter E_c and the potential at the emitter end of the base O_{be} are indicated.

We discuss these results in light of earlier investigations of hot electron injection into uniformly doped base devices and Levi et al's calculations for the energy loss rate for hot electrons in p-type material. For the case of hot electron injection into a uniformly doped base, with an initial hot electron excess energy (energy step at emitter/base junction) of 0.20eV, comparable to the net potential energy gain available to electrons in the graded bandgap base, we found that the electron distribution cooled as the electrons traversed the base to yield T_e=350K for a base width of 45nm and 120K for a base width of 90nm. These results are consistent with the calculations that finds the energy loss rate for hot electrons varies with average energy but is in the range of 0.05ps for energies in the range of 0.1eV. In the present experiments we find for a base width of 90nm and a net energy gain in transiting the base of 0.18eV an electron temperature of 650K. While this is a factor of four times the temperature obtained in earlier experiments, this is still well below the maximum temperature expected for the case where electron-hole scattering is neglected. The temperature rise is limited by the onset of intervalley scattering at higher energies. Levi et al. have calculated significantly greater energy loss rates for minority hot electrons in p-type material ($p=2x10^{18}cm^{-3}$). In the present case the continuous acceleration of the electrons by the quasi-electric field results in a dynamic equilibrium in which the electron distribution can be maintained at a significant average temperature (650K vs. 120K after traversing 95nm). This result can be understood if we consider the average energy gain from the quasi-electric field between energy loss collisions. For an average energy of 60meV Levi et al calculate a collision time of 0.05ps or a mean free path of approximately 30nm. The average energy gained from the quasi-electric field in traversing this distance is about 60meV. Thus unlike the case of hot electron injection, in this case the injected electrons continuously loss energy as they come into equilibrium with the sea of holes in the base, in this case the electrons gain energy continuously from the quasi-electric field and come into equilibrium with the combined quasi-field/hole sea after traversing a distance of 27.5nm and gain a net energy of 60meV. At this point the rate of energy gain from the quasi-electric field is just balanced by the rate of energy loss to the holes and the electron temperature remains relatively constant the rest of the way across the graded region.

In conclusion we have measured the hot electron spectra of minority electrons traversing the base of a graded band gap heterojunction bipolar transistor and have found that the dynamics of energy exchange between the minority carriers and the background sea of holes is quite different than the case of hot electrons in a uniformly doped base structure. We find an electron temperature of 650K, nearly four times larger than that obtained for minority electrons with comparable potential energy gains after transiting comparable base widths in uniformly doped devices. This significant difference is shown to be consistent with calculated energy loss rates.

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