High-Resolution Hot-Electron Spectroscopy in Parallel Magnetic Fields

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Hot-carrier spectroscopy is a well established technique to analyze band structure and transport properties of semiconductor bulk and heterostructure material systems. In previous works, this technique was applied to observe ballistic electron and hole transport in bulk GaAs [1], [2], to map miniband positions of finite superlattices [3] and to determine the transition from coherent to incoherent electron transport in GaAs/AlGaAs superlattices [4]. The technique was also used to demonstrate electron transport enhancement through superlattices with antireflection coatings [5]. Recently, the resolution of the spectrometer could be improved considerably to 10 meV [6]. Utilizing this improved design of the hot-electron transistor, the Wannier–Stark splitting and the progressive localization of individual Wannier–Stark states could be observed separately in short superlattices [7].

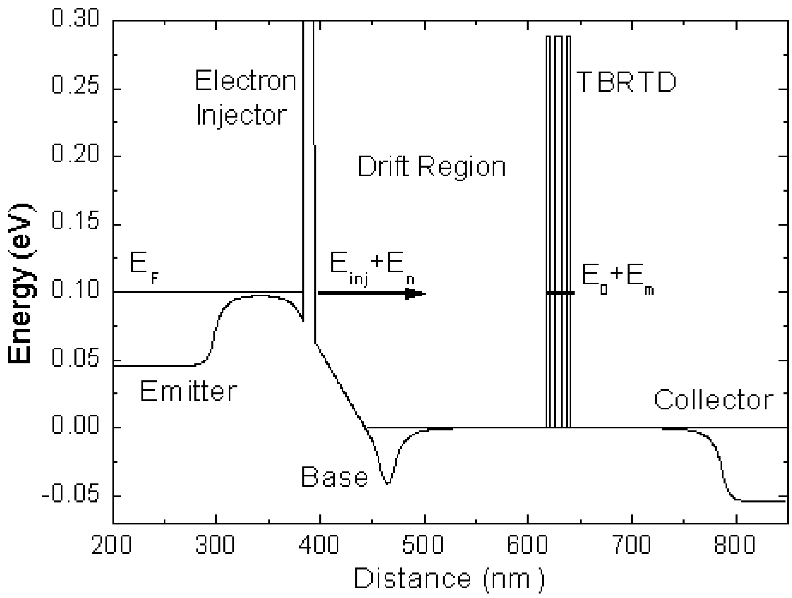

Fig.1: Conduction-band diagram of a three-terminal device along the growth direction incorporating a triple-barrier RTD between the base and collector.

In this work, we focus on the situation where the magnetic field is applied parallel to the current direction which is identical with the growth direction [8]. Figure 1 shows the calculated conduction band structure of the hot-electron transistor presented in Ref. [6]. An energy tunable electron beam is generated by the emitter tunneling barrier (emitter current I_E) and reaches a triple-barrier RTD (TBRTD) with a normal-energy distribution of 17 meV in width after traversing a highly doped *n*-GaAs base layer and a slightly *n*-doped GaAs drift region. Electrons which are transmitted through the RTD are measured as collector current I_C. Reflected electrons are collected in the base contact and do not contribute to I_C. Due to the sharp filter characteristic of the TBRTD (E_0 =

100 meV, FWHM =1 meV), the measured transfer ratio $\alpha=I_C/I_E$ is directly proportional to the superposed energy distributions of the ballistic electrons and of the phonon replicas [6].

In the presence of a magnetic field applied parallel to the current direction, all electronic states are quantized in the plane perpendicular to the magnetic field direction into Landau levels of energies $E_n = \hbar\omega_c (n+1/2)$ where n denotes the Landau-level index and $\hbar\omega_c= \hbar eB/m^*$ the Landau splitting. At injection energies where the corresponding Landau levels of the injector and the RTD are aligned ($E_{inj} = E_0$), we get resonant magnetotunneling of ballistic electrons through the GaAs drift region and the RTD. In the absence of elastic or inelastic scattering, inter-Landau-level transitions are forbidden. In the hot-electron transistor, the Landau-level conservation is lifted by inelastic longitudinal optical (LO)-phonon scattering and by elastic scattering processes (charged impurity scattering and electron–electron scattering) in the GaAs drift region. As a consequence the individual peaks in the transfer ratio (ballistic peak and phonon replica peaks) build up satellites shifted by $\Delta n\hbar\omega_c$ according to electrons which changed the Landau-level index by Δn during the scattering process.

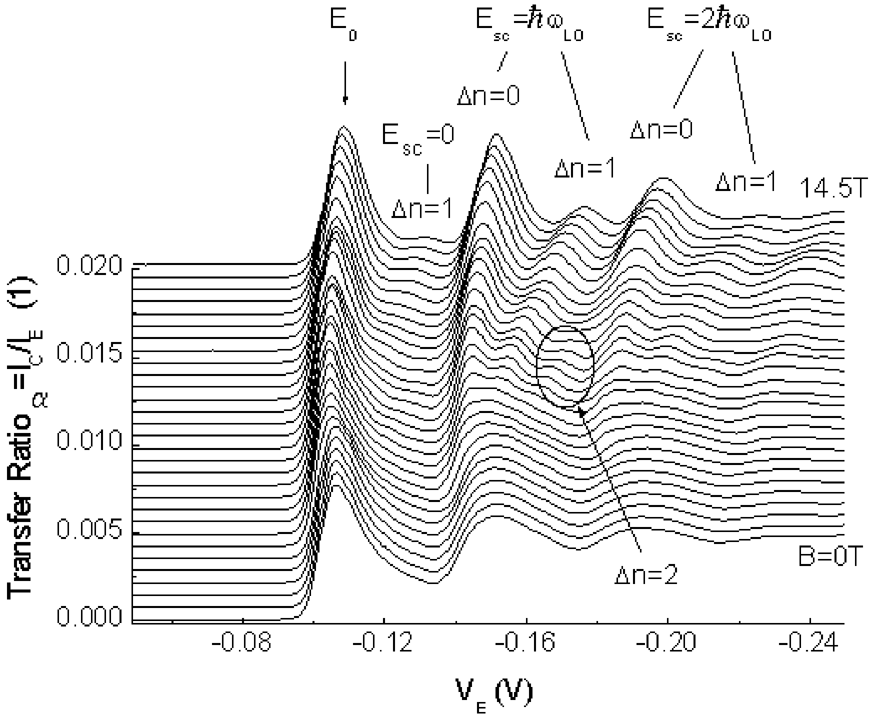

Fig. 2: Transfer ratio vs. emitter bias of the TBRTD at magnetic fields up to 14.5 T in steps of 0.5 T.

Figure 2 shows the measured transfer ratio of the TBRTD as a function of the emitter bias at different magnetic fields up to 14.5 T in steps of 0.5 T. The first peak indicated by 'E_0' is attributed to resonant magnetotunneling ($\Delta n = 0$) of hot electrons through the RTD. On the low-energy tail, weak satellites are observed which are equally spaced by $\hbar\omega_c$. Since these peaks are observed well below the energy of the first phonon replica, this is direct evidence of the elastic scattering induced breakdown of the Landau-level conservation. The same splitting is observed in all phonon replicas which is direct evidence of the inelastic scattering induced breakdown of the Landau level conservation by LO phonons.

The peaks which correspond to resonant magnetotunneling $\Delta n = 0$ exhibit nearly no shift with magnetic field due to the collective Landau quantization of all electronic states in the device. The weak dependence of the peak position on magnetic fields is due to (i) magnetic depopulation effects at the emitter side of the injection barrier and (ii) a magnetic field dependent series resistance in the base contact. The peaks which correspond to scattering-assisted inter-Landau level transitions of $\Delta n = 1, 2$ are showing a clear magnetic field dependence. Due to the overlap of the peaks in the transfer ratio, the Landau-level spacing $\hbar\omega_c$ can only be resolved at magnetic fields where the individual peaks are sufficiently separated in energy. From Fig. 2, it follows that the peaks are resolved at magnetic fields higher than 6 T which equals a cyclotron energy of $\hbar\omega_c = 9.4$ meV. This value for the resolution corresponds to the half width at half maximum (HWHM) of $\Delta V_E = 7.8$ mV of the ballistic peak at 6 T.

In conclusion, the performance of a hot-electron transistor in parallel magnetic fields up to 14.5 T has been studied. A triple-barrier RTD with a narrow energy window of 1 meV at $E_0 = 100$ meV was used to scan the energy distributions of the injected electron beam and of the phonon replicas. Scattering-induced inter-Landau level transitions are observed in the ballistic electron peak due to elastic scattering in the highly doped base contact layer as well as in the phonon replicas due to LO-phonon scattering in the drift region of the hot-electron transistor. This way it is possible to study the strength of elastic and inelastic scattering mechanisms simultaneously in a single device.

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