Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 443-445

Current Oscillation with an InAs/AlSb Resonant-Tunneling Diode Measured at 77K

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We have successfully fabricated an asymmetric AlSb/InAs/AlSb resonant-tunneling diode which generates a chain of current pulses with novel operational mechanisms, i.e., successive energy loss of hot electrons by emission of LO phonons. To our knowledge, this is the first direct demonstration of clear current peaks of multiple phonon replica with the current amplitude of approximately $1.25 A/cm^2$. We have also observed current peaks which seem to originate from Γ-X inter-valley tunneling.

1.Introduction

There have been many experimental reports on ballistic electrons in solids[1-5]. However, successful electrical experiments were done using device structures with single-barrier analyser[2] or even no barrier at the collector side[1]. The current pulse amplitudes of these devices were extremely small. One can expect much higher peak-to-valley ratio of the phonon replica if there were ideal resonant-tunneling-diode (RTD) analyser. RTD analyser based on (AlGa)As/GaAs heterostructure suffers from severe leakage current due to relatively low conduction band discontinuity between Γ-valley of GaAs and X valleys of (AlGa)As.[4-5]. On the other hand, AlSb/InAs/AlSb heterostructures are attracting interests for their higher low-field mobility, higher energy separation of the subbands, higher-lying satellite valleys, higher conduction band discontinuity and subsequent strong confinement of electrons in the quantum well [6-10]. Because of this strong confinement nature and the low effective mass of electrons in the InAs well, quantum effects of not only the confined electron systems but spectrum of the ballistic electrons are expected to be obtained directly at relatively high temperatures where thermal broadning makes energy band-width of the ballistic electrons as wide as optical phonon energy of InAs (≈30meV). In this report, the energy spectrum of the ballistic electrons emitted from the 2DEG will be analysed through the InAs/AlSb double barrier resonant tunneling diode (RTD).

2.Experimental

The heterostructure of the devices were grown by molecular beam epitaxy. As shown in Fig.1, it consists of 2000 Å of GaAs buffer layer grown on undoped GaAs substrates, 8000Å of AlSb buffer layer, 4000Å InAs layer, 70 Å of AlSb, 50 Å of InAs, 70 Å of AlSb , and 500 Å of InAs layer. Although there is no intentiopnal doping, deep donors of approximately $10^{17} cm^{-3}$ exist[11-12] in the AlSb buffer layer. It is believed to be originated from the residual oxigen in the solid antimony source[11]. In order to maximize the AlSb/InAs interface quality, the crystal growth has been performed in such a way as to form InSb-bonding at the AlSb/InAs interface[6,12]. Thus, inverted modulation-doped structure is naturally formed in InAs near the interface between InAs buffer layer and AlSb buffer layer. The fabrication process of the device is similar to InAs/AlGaSb quantum effect devices[9-10]: device isolation was done by mesa-etching, non-alloyed ohmic contact were formed by directly depositing Ti/Au on both top and buried InAs layers. The schematic cross-sectional diagram of the device is shown in Fig.2. The current path under positive bias is designated by the arrows in the figure assuming that most of the current passes through the two-dimensional-electron-gas (2DEG) for simplicity. However, there possiblly exist current components that pass though InAs bulk. Basically, the device consists of two parts: one is AlSb/InAs inverted modulation-doped heterostructure and the other is AlSb/InAs/AlSb double barrier resonant tunneling diode. The 2DEG becomes an injector and the injected electrons transit through the InAs layer where some of them lose energy by emitting LO phonons InAs/AlSb RTD spectrum analyser, then collected by the top electrode which makes non-alloyed ohmic contact to InAs top layer. Schematic energyband diagram under positive bias is shown in Fig.3. We have also performed magnetoresistance measurements on the samples at low temperatures which will be discussed in the next section.

3.Results and Discussions

The current voltage characteristics of positively biased region at 77K is shown in Fig.4. There are two distinct voltage regions where small structures are observed. One is the voltage region below the main peak where three subpeaks are observed. Let it be called 'region I'. The other voltage region of interest is beyond the main peak, where small peaks (five peaks in the present figure) are observed with the period of approximately 60meV. Let this region be called 'region II.' The main peak is of course the resonance tunneling current through Γ-valley quasi-bound state of electrons in the InAs quantum well. The subpeaks in 'region I' are attributed to inter-valley scattering such as $\Gamma\text{-}X_t\text{-}\Gamma\text{-}X_t\text{-}\Gamma$ or $\Gamma\text{-}X_l\text{-}\Gamma\text{-}X_l\text{-}\Gamma$ where subscripts t and l denotes transverse and longitudinal direction, respectively, in the ellipsoids of the satellite valley. Two facts support the model of inter-valley tunneling. One is the reasonably good agreement between the experimental results (black symbols in Fig.5) and the calculation (white circles in Fig.5) of the resonance energy of Γ-X inter-valley tunneling. The other is the current peak positions dependence on magnetic fields. Let us closely look at the results one by one. As for the resonance energy calculation, most of the peak positions agree well with the calculational results taking account of the effective mass difference in the barrier materials as shown in Fig.5 except for the lowest peak which is unassigned. The slight departure of the data from calculation at higher biases are presumably caused by the voltage drop at parasitic resistances of the device at higher current. Figure 6 shows the conductance dependence on magnetic fields. Peak position in 'region I' just barely moves towards higher bias as the magnetic field increases whereas main peak and the rest of the current peaks in 'region II' move more strongly toward higher bias with magnetic fields. It indicates that the heavier effective mass of electrons are involved in the peaks of 'region I' suggesting Γ-X inter-valley scattering. However, they are still controversial both in GaAs/AlGaAs and InAs/AlSb system.[14-16]

The current oscillations observed in 'region II' have periods of twice as much as LO phonon energy in InAs as shown in Fig.4. Similar results were obtained in number of different samples. However, the question of whether or not the period is really $2h\omega/2\pi$ remains unsolved. Reasonably good agreement of calculation and the experimental result of the subpeaks in 'region I' suggests that that the maesured voltage is close to the real energy of the ballistic electrons suggesting double phonon emission. Thermal broadening may explain

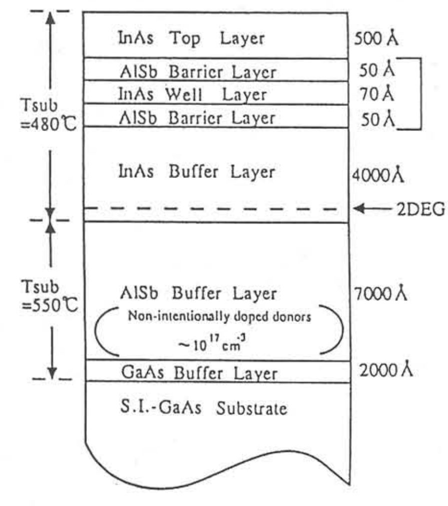

Figure 1. Schematic heterostructure diagram of the InAs/AlSb RTD device.

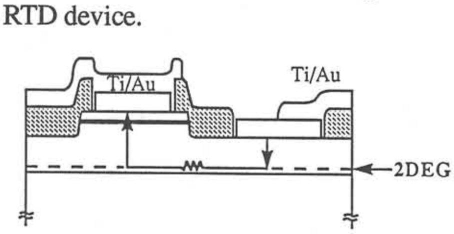

Figure 2. Schematic cross-section of the InAs/AlSb RTD device. Lateral device size ranges from 2μm to 50μm square.

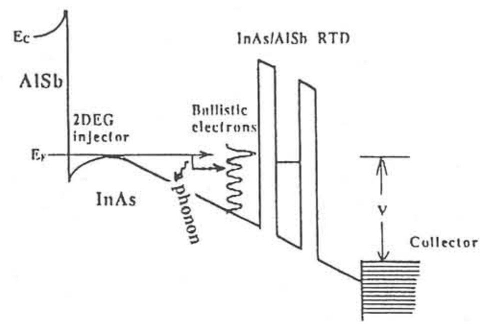

Figure 3.Schematic energyband diagram of the InAs/AlSb RTD device.

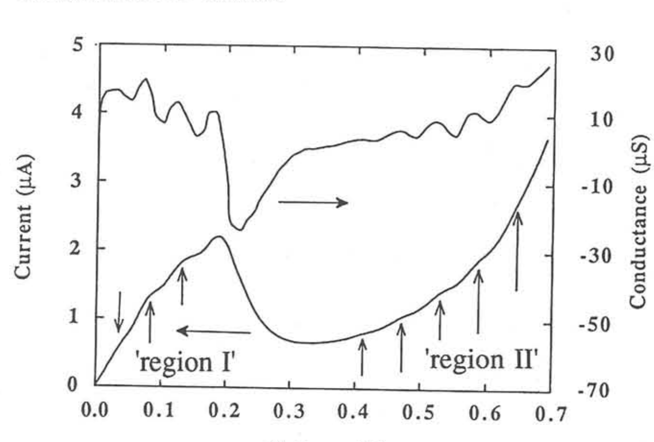

Figure 4. Current voltage characteristics of the InAs/AlSb RTD device.

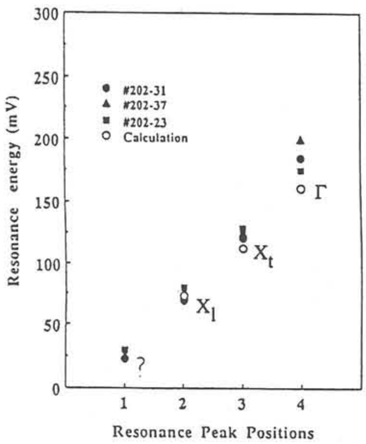

Figure 5. Comparison of the calculated resonance energy of Γ-X inter-valley tunneling and measured nergy spacing of subpeaks in 'region I'.

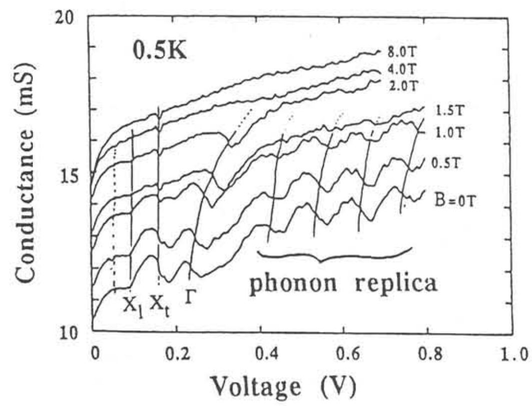

Figure 6. Conductance dependence on magnetic fields of sample #202-98.The lateral device size was $50\mu m$ square.

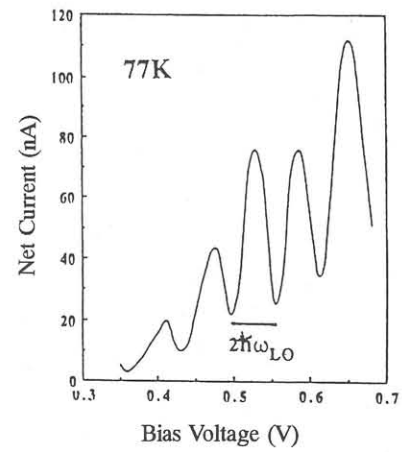

Figure 7. The net peak currents of phonon replica in sample #202-23 . The lateral device size was $2\mu m$ □.

why single phonon emissions were hardly observable. The other possibility is that the measured voltge drop was twice as large as the real electron energy assuming that the voltage drop across the current path is almost completely supported by the AlSb barrier layers. If it were true, the energy spacing becomes 30meV which is exactly single LO phonon energy in InAs. However, one should explain why the calculation and experimental results agreed well in resonance peaks in 'region I'. These questions should be clarified in the future. In any case, the phonon replica observed in the present InAs/AlSb system is very clear and reproducible. Magnetoresistance measurements also supports that the peaks are phonon replica because the subpeaks in 'region II' shift together with the main peak as the magnetic field increases in Fig.6. The net peak currents were obtained by subtracting the backgroung currents from the measured current as shown in Fig.7. It would be interesting to have such a current pulse generator which works with a new mechanism: LO phonon emission. The present result showing direct observation of phonon replica at least confirms the powerful potential of the InAs/AlSb RTD as a spectrum analyser of ballistic electrons.

4.Conclusion

We have successfully fabricated an asymmetric AlSb/InAs/AlSb resonant-tunneling diode which generates a chain of current pulses with novel operational mechanisms, i.e., successive energy loss of hot electrons by emission of LO phonons. To our knowledge, this is the first direct demonstration of clear current peaks of multiple phonon replica with the current amplitude of approximately $1.25A/cm^2$.

Acknowledgements

The authors are grateful to Y.Yamamoto for the technical assistance in the device fabrication and measurement. This work was partially supported by Grant-in-Aid for Scientific Research from The Ministry of Education, Science and Culture.

*Presently with NEC Corporation.

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