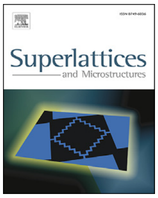
Superlattices and Microstructures 103 (2017) 121–126

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices



Electrical measurement of the linewidth of a quantum well bound state

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ARTICLE INFO

Article history:
Received 10 January 2017
Accepted 14 January 2017
Available online 18 January 2017

Keywords:
Quantum well
Resonant tunneling diode
Tunneling spectroscopy

ABSTRACT

We investigate electron tunneling spectroscopy in the presence of a bound state within a double quantum barrier, single quantum well structure. We demonstrate a new technique to directly measure the intrinsic linewidth of the bound state within the quantum well from the current-voltage signature of the resonant tunneling phenomena and contrast our results with the standing approach in the literature. We then examine the signal behavior for the influence of device temperature and find support for electron-electron interactions within the well. The measured intrinsic bound-state width, Γ_E, in the negative differential conductance regime is 1.11± 0.01 meV.

1. Introduction

1.1. Motivation

In the transition from the macroscopic to the mesoscopic, changes in electron dimensionality have given rise to exotic device physics exploiting electron confinement to modify the transport physics. Researchers made use of tunneling spectroscopy into and through bound states for a variety of different device geometries: 3D-0D-3D [1,2], to and from two-dimensional electron gas (2DEG) into 2D and 0D states [3–5], as well as 3D-2D-3D processes in semiconductor heterostructures [6].

Tunneling via an intermediary bound state present in the system gives rise to a peak in conductance [1,2] when incoming electrons have energies corresponding to that of the bound state. The work of Tsuchiya et al. [6], established an analogous signature in the second derivative of the current-voltage characteristic of the tunneling current for a double quantum barrier, single quantum well (DQB) system. Because this signature occurs at the onset of appreciable current passing through the device (corresponding to minimal accumulated charge density within the well region), this technique claims to measure the intrinsic properties of the bound state within the quantum well, a notion that has propagated throughout the literature [7–9].

We propose and subsequently demonstrate a new application of tunneling spectroscopy to measure the bound state parameters in the negative differential conductance regime of the DQB structure, and show that these parameters are markedly different from those extracted via the existing approach. Our technique should prove useful for researchers seeking

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http://dx.doi.org/10.1016/j.spmi.2017.01.017
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non-destructive characterization of double quantum barrier (also known as resonant tunneling diode) structures for terahertz oscillator applications [10].

2. Materials & methods

To investigate an idealized case of resonant tunneling through a bound state, a previously-characterized [11] double-barrier GaAs-AlGaAs resonant tunneling diode was studied.

Current-voltage measurements were taken with a HP 4156B semiconductor parameter analyzer. Harmonic detection of derivatives of the current was accomplished with two SRS830 lock-in amplifiers monitoring the first and second harmonics, respectively. A Yokogawa 7651 voltage source and Agilent 33210A function generator provided the DC bias and excitation signal, respectively, to custom-made voltage summer circuitry before being supplied to the device. The bias voltage was increased in a step-wise manner for all device scans with a DC ramp rate never exceeding 0.5 mV/s.

All measurements were conducted with the sample positioned inside a Janis SVT-100 continuous vapor flow cryostat. Sample temperature was controlled by flowing liquid helium through a heater-wound capillary. Activation of the PID-controlled heater resulted in warm helium vapor flowing over the device.

3. Theory

3.1. Tunneling spectroscopy

Here we utilize tunneling current measurements to directly examine the electronic properties of a bound state, engineered in a classic double quantum barrier, single quantum well system, as shown in Fig. 1 (a). The conduction band of the double-barrier heterostructure forms a confining potential, producing the quantum well bound state. The energy of conduction electrons in the source align with the bound state under applied bias, shown in Fig. 1(b), resulting in resonant tunneling through the bound state [12].

The onset of resonant tunneling produces a rise in device current followed by a steep drop as the applied bias pushes the bottom of the conduction band beyond the resonant state, as seen in Fig. 2(a). To elucidate the shut-off of resonant tunneling, we also plot the conductance, G (Fig. 2(b)), and dG/dV (Fig. 2(c)). We observe that the dG/dV signal gives a sharp measurement of the shut-off width. Further on, we will compare how this feature corresponds to the quantum well bound state lifetime, and compare that to the linewidth derived from the resonant activation previously investigated in the literature [6].

Modelling the tunneling barrier as a scattering region, the current flowing through the device depends upon the energy distribution of incoming electrons in the source (the supply function), the transmission function of the active region of the device, and the availability of states in the drain into which electrons can tunnel [13,14]:

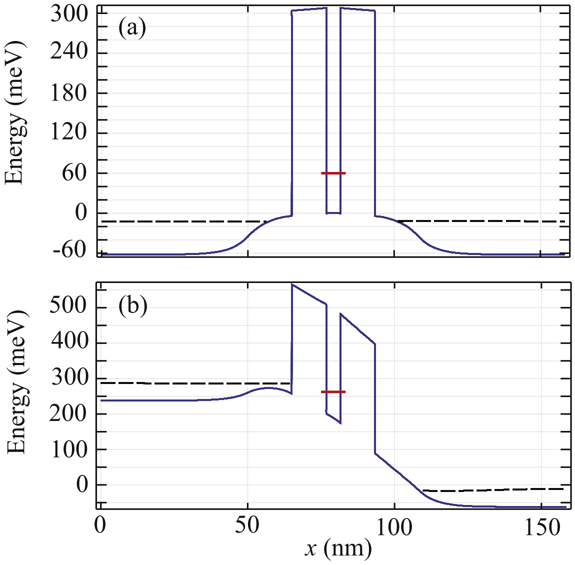

Fig. 1. COMSOL-generated plots of the self-consistent band diagrams (blue) and quasi-equilibrium Fermi energies (black, dashed) for the device under test (a) at equilibrium and (b) biased to the point of shut-off for resonant tunneling. The lowest-energy bound state is illustrated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)