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Title: PIEZOELECTRIC EFFECTS IN DOUBLE BARRIER RESONANT TUNNELING STRUCTURES

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PIEZOELECTRIC EFFECTS IN DOUBLE BARRIER RESONANT TUNNELING STRUCTURES*

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ABSTRACT

It is shown that piezoelectric effects can give rise to internal electric fields that modify the conventional current vs. voltage characteristics of III-V semiconductor double barrier resonant tunneling devices, if suitable stresses are applied. We measured current vs. voltage characteristics of symmetric, (001)-oriented AlAs/GaAs/AlAs double barrier structures as a function of external stress. Uniaxial stress was applied parallel to the (110), the $(1\bar{1}0)$, and the (001) directions. In order to understand the experimental results we calculated the current vs. voltage characteristics of resonant tunneling structures under uniaxial stress, including pressure effects on the band alignment and the effects associated with the piezoelectric nature of the constituent materials. Stresses along the (110) or $(1\bar{1}0)$ directions give rise to polarization charges at the interfaces, due to differences in the piezoelectric constants of the materials. The resulting internal electric fields are found to modulate the I-V characteristics, in good agreement with our experimental data.

1. Introduction

Double barrier resonant tunneling devices are of considerable interest for a variety of ultra-high frequency and logic switching applications. Typically, the structures consist of GaAs with AlGaAs barrier layers grown on (001)-oriented GaAs substrates. Their resonant tunneling I-V characteristics have been studied as a function of hydrostatic pressure[1] and uniaxial stress along the direction parallel to the current.[2] The observed modulation of the I-V curves under pressure was successfully explained by deformation potential induced shifts in the relative alignment of the central and satellite valleys.

In this paper we discuss a novel modulation of the I-V characteristic under uniaxial stress applied along either the (110) or $(1\bar{1}0)$ crystal axes perpendicular to the current. For this type of stress geometry a polarization field oriented along the (001) crystal axis arises due to the piezoelectric nature of the III-V semiconductors that compose the double barrier structure. However, even if the strain field is uniform, the polarization will be different in the well, barrier, and cladding layers due to the different piezoelectric constants of the constituent materials. Consequently, polarization charges at the interfaces, and electric fields associated with these charges, will exist within the double barrier structure under stress. These electric fields have a significant impact on the current vs. voltage characteristics.

2. Experiment

The samples were grown in a gas source MBE Riber 32P system on (001)-oriented n^+ GaAs substrates. The undoped double barrier structures consisted of 5.0nm thick AlAs barriers separated by a 5.7nm GaAs well. To minimize unintentional doping, the double barrier was separated by 20nm and 40nm thick undoped spacer layers on surface and substrate side, respectively, from the Si-doped ($n_D = 10^{18}$ cm^{-3}) GaAs cladding regions. The entire structure was grown at 590° C, growth was interrupted for seven seconds at each heterointerface to smooth the surfaces.

Circular dots with diameters of 100µm, 200µm, and 400µm were formed by photolithography. Ni/Ge/Au was used as contact materials on both the front and back sides to form the ohmic contacts. 4µm high mesas were wet-etched on the front side to isolate the devices.

We measured current vs. voltage characteristics at 77K. Stress was applied along three orientations (110), ($1\bar{1}0$), and (001) with an apparatus described previously[2]. Fig. 1 shows the I-V curves of a 200µm diameter device at zero stress and under 3.39 kbar along (110). The current peaks and valleys appear at rather large absolute voltages because of the voltage drops across the wide, undoped spacer layers (series resistance). Clearly, the resonances in both the forward and reverse direction shift towards more positive voltages. Conversely, shifts towards more negative resonance voltages are observed if the stress is applied along the ($1\bar{1}0$) direction, as shown in Fig. 2. For stresses

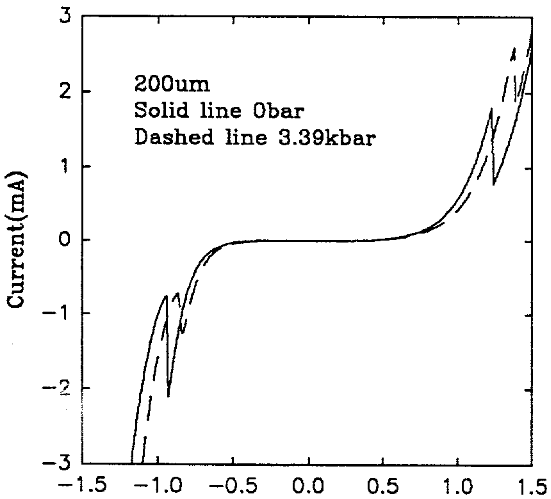

Fig. 1. Measured I-V curves under stress along the (110)-orientation at 77K.

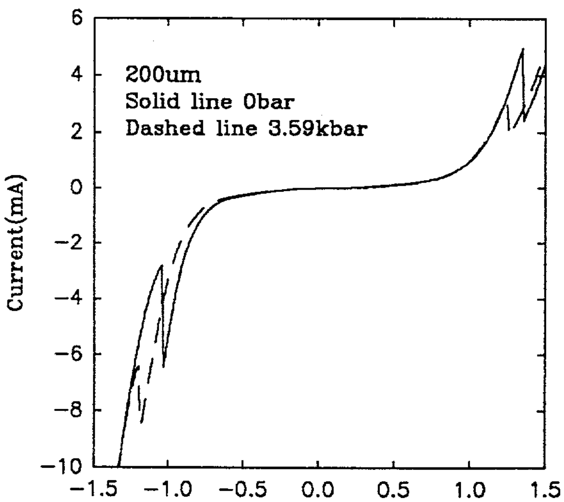

Fig. 2. Measured I-V curves under stress along the ($1\bar{1}0$)-orientation at 77K.

along (001) we found small, symmetric shifts of the resonances in both forward and reverse direction similar to those reported earlier.[2] The results for the resonance voltage in reverse direction as a function of stress in the three different directions are summarized in Fig. 3. The measured peak voltages do not coincide for zero stress because the constraints imposed by the experimental apparatus require the use of different samples for the different stress orientations.

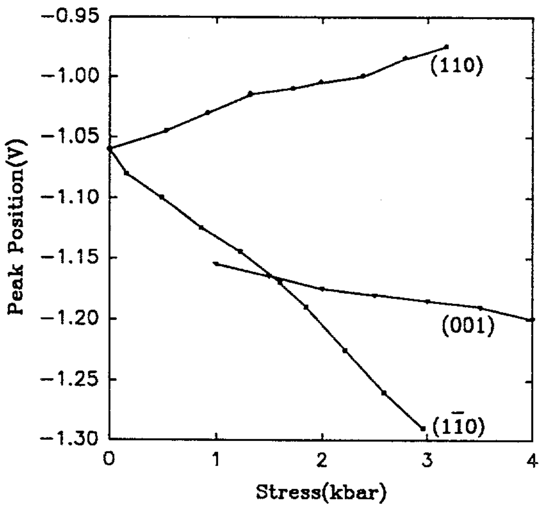

Fig. 3. Measured resonant peak voltages under reverse bias as a function of uniaxial stress.

3. Theory

In order to be able to interpret our experimental data we calculated current vs. voltage characteristics as a function of transverse stress. The transmission coefficient was calculated in an effective two band model by discretizing the barrier and well layers into segments with constant potential and then matching plane waves at the potential steps. Self-consistent band profile calculations treated the accumulation and depletion layers near the barriers in a finite temperature Thomas-Fermi approximation. The current was then determined by integrating the transmission coefficient.[3]

For all three orientations of external stress ((110), (1$\bar{1}$0), and (001)) the strain distribution throughout the mesa was assumed to be equivalent to the strain of the substrate. For example under (110) stress, the non-vanishing off-diagonal strain tensor component is:

$$\varepsilon_{xy} = \frac{P}{\sqrt{8}} C_{44} \tag{1}$$

where P is the pressure and C_{44} is the relevant stiffness constant of the GaAs substrate. The deformation potential induced band shifts associated with the external stresses were calculated using the "model-solid" approach of Van de Walle.[4]

The piezoelectric effect manifests itself through interfacial polarization charges given by $2\varepsilon_{xy}[e_{14,i} - e_{14,j}]$ for the interface between the i-th and j-th layers. ε_{xy} is the off-diagonal strain tensor component from eqn. (1) and $e_{14,i}$ is the local piezoelectric constant of the i-th layer. The structures modeled differed from those experimentally investigated in barrier composition and in the absence of undoped spacer layers. Barrier and well thicknesses were the same. Fig. 4 shows a calculated band diagram for a (001)-oriented $Al_{0.4}Ga_{0.6}As/GaAs/Al_{0.4}Ga_{0.6}As$ double barrier structure under zero stress and 10kbar of stress along the (110)-direction. The magnitude of the polarization charge densities is approximately 1.5×10^{11} electrons/cm^2. The effect of these interfacial charges is seen in the I-V characteristics of the device. The net internal electric field caused by the polarization charges opposes the external electric field under forward bias (electron flow in positive z-direction). Therefore, the resonance peak in the I-V is shifted to a more positive voltage. This shift is expected to be approximately given by the product of the total thickness of the double barrier structure and the net internal field (~30mV in the example discussed here), if the deformation potential effects are ignored. In a completely analogous manner, the interfacial charges for $(1\bar{1}0)$ pressure have the opposite sign and contribute an electric field which adds to the applied field under forward bias. Hence the resonances shift towards more negative voltages. Fig. 5 shows the calculated I-V characteristics of this structure for zero stress and under 5kbar along the (110)-direction and along the $(1\bar{1}0)$-direction.

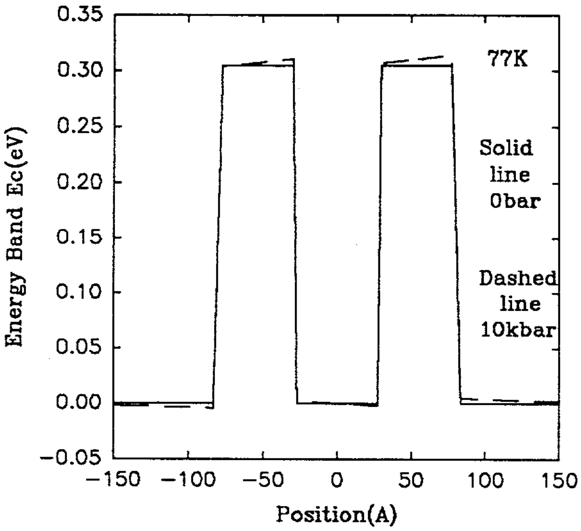

Fig. 4. Calculated band diagram of double barrier structure under zero stress and under 10kbar stress along (110).

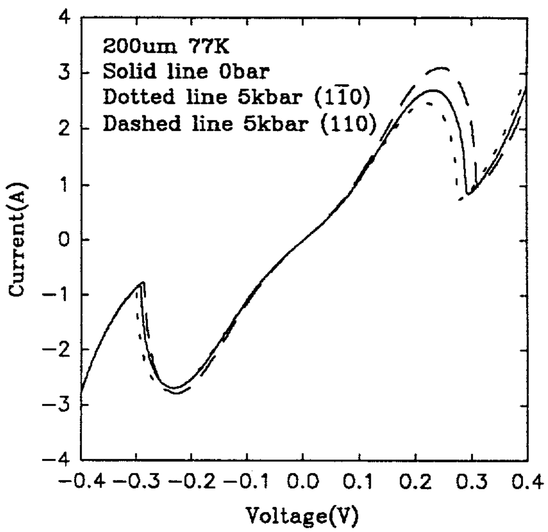

Fig. 5. Calculated I-V characteristics under zero stress and 5kbar stress along the (110) and $(1\bar{1}0)$-orientations.

In summary, we observed a novel stress modulation of the current vs. voltage characteristics of (001)-oriented GaAs/AlAs double barrier resonant tunneling devices. We associate the effect with the piezoelectric nature of the constituent materials and find good agreement between predictions of a model based on this hypothesis and the experimental data. We speculate that given proper optimization, this effect may lend itself to the implementation of novel devices that sense strain, e.g. that associated with a surface acoustic wave.

4. References

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