Mesopiezoresistive effects in double-barrier resonant tunneling structures

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This letter reports a mesopiezoresistive effect in a double-barrier resonant tunneling (DBRT) structure. In a DBRT system, an external mechanical stress causes a tensile strain, and the strain, in turn, affects the resonant tunneling and thereby the resistance. Theoretical analysis was carried out on an AlAs/GaAs/AlAs DBRT structure under in-plane uniaxial tensile stresses. The results show that the tunneling current and resistance of a DBRT structure change significantly with external stress-induced tensile strains. The results also show that the resistance-strain response can be tuned effectively by the external voltage. The effect has potential applications in miniature electromechanical devices. © 2008 American Institute of Physics. [DOI: 10.1063/1.2839316]

The change of resistance of a material due to an externally applied mechanical stress is called a piezoresistive effect. In contrast to the piezoelectric effect, the piezoresistive effect only causes a change in resistance; it does not produce electrical charges. In 1954, Smith discovered large piezoresistive effects in silicon and germanium.\textsuperscript{1} Since then, the piezoresistive effect of semiconductors has been widely used for sensor devices. These devices include microphones, actuators, piezoresistors, accelerometers, and pressure sensors, among others.

This letter addresses a piezoresistive effect in a double-barrier resonant tunneling (DBRT) structure. It is known that the tunneling current of a DBRT structure depends on the potentials and widths of the barriers and wells, as well as the externally applied bias voltage. If one applies a uniaxial stress on the structure, the widths of the barriers and wells will change. This change, in turn, can result in changes in the tunneling current and current-voltage (I-V) response of the structure. As a result, one can expect the tuning of the resistance of the DBRT structure by external mechanical stresses. In this letter, such a mechanical tuning of the resistance of DBRT systems is called a “mesopiezoresistive effect,” in contrast to the above-mentioned classical piezoresistive effect.

It is important to emphasize that the potentials of the barriers and wells also change with the external stress. Theoretical calculations indicate, however, that the influence of the stress-induced potential change on the tunneling current is insignificant in comparison with the effect of the strain-induced thickness change.\textsuperscript{2,3} It is also important to note that the piezoresistive effect described in this letter differs from the piezoelectric effect described in this letter, where interfacial polarization charges arise due to the externally applied stresses.\textsuperscript{4-6}

Specifically, in this letter, a theoretical analysis of the effects of external stress-induced tensile strains on the resistance of AlAs/GaAs/AlAs DBRT structures is reported. The tunneling currents and piezoresistive coefficients are calculated as a function of the tensile strain in the structures as well as of the external bias voltage. The calculation is based on the resonant tunneling theory,\textsuperscript{7-9} which was initially developed by Tsu and Esaki.\textsuperscript{7} The results indicate that the mesopiezoresistive effect has potential applications in electromechanical devices that are small in size and demand low power consumption.

Figure 1 shows a (001) oriented AlAs/GaAs/AlAs resonant tunneling structure on the left and its potential profile on the right. The \( z \) axis is perpendicular to the plane of the structure and thus parallel to the [001] direction of the structure. The structure is symmetric along the \( z \) axis, and the two barriers have the same height of \( V_b \) and the same width of \( L_B \). The well has a width of \( L_W \). If an electron wave is incident on this system from the left, it will be partially reflected from and partially transmitted through the system. If one assumes that the incident wave has an amplitude of one, the reflected wave has an amplitude of \( R \), and the transmitted wave has an amplitude of \( \tau \), one will have the following expression:

\[
\begin{pmatrix} \tau \\ 0 \end{pmatrix} = M \begin{pmatrix} 1 \\ R \end{pmatrix},
\]

where the transfer matrix \( M \) is determined by

\[
M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix},
\]

\[
\begin{pmatrix} \tau \\ 0 \end{pmatrix} = M \begin{pmatrix} 1 \\ R \end{pmatrix},
\]

\[
M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}.
\]

FIG. 1. Left: AlAs/GaAs/AlAs resonant tunneling structure. Right: the potential profile of the structure shown on the left. Labels \( V_b \), \( L_B \), and \( L_W \) denote the barrier amplitude, barrier width, and well width, respectively. Labels 1, \( R \), and \( \tau \) denote the amplitudes of the incident wave, reflected wave, and transmitted wave, respectively.

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\[ M_{11} = \left[ \frac{\alpha^2 - \beta^2}{2\alpha\beta} \sinh(\beta L_B) + \cosh(\beta L_B) \right] \exp(i\alpha L_W), \]
\[ M_{12} = -\frac{\alpha^2 + \beta^2}{2\alpha\beta} \sinh(\beta L_B) \exp(i\alpha L_W), \]
\[ M_{21} = M_{12}^*, \]
\[ M_{22} = M_{11}^*, \]
(2)

where \( \alpha = \sqrt{2mE/\hbar} \) and \( \beta = \sqrt{2m(V_0 - E)/\hbar} \). In these equations, \( m \) is the electron effective mass, \( E \) is the electron energy, and \( \ast \) denotes the complex conjugate operation.

The above equations allow for the determination of the transmission coefficient of the structure, which is given by \( \tau^\ast \tau \). The transmission coefficient, in turn, allows for the calculation of the tunneling current density as
\[ J = \frac{e^m k T}{2\pi^2 \hbar^3} \int_0^\infty \tau^\ast \tau \ln \left( 1 + \exp \left[ \frac{(E_f - E)/kT}{1 + \exp \left[ (E_f - E - eV_a)/kT \right]} \right] \right) dE, \]
(3)

where \( e \) is the electron charge, \( k \) is the Boltzmann constant, \( T \) is the temperature, \( E_f \) is the Fermi energy, and \( V_a \) is the externally applied bias voltage.

With the above equations, one can calculate the tunneling current density \( J \) and the resistance coefficient \( r = V_a / J \) as a function of the external bias voltage \( V_a \). One can also use these equations to analyze the effect of external stresses on the resistance of the DBRT structure. From the device application point of view, it is appropriate to consider the application of a uniaxial tensile stress in the plane of the DBRT structure. This external stress can affect the resistance of the structure. Through such a process, one can expect the tuning of the resistance of the DBRT structure through external stresses.

Assuming a tensile strain of \( \varepsilon \) along an in-plane uniaxial stress, the decrease in the barrier width \( L_B \) and the well width \( L_W \) can be expressed as
\[ \delta = \frac{2C_{12}}{C_{11}} \varepsilon, \]
(4)

where \( C_{11} \) and \( C_{12} \) are the elastic moduli of the barrier and well materials in the coordinate shown in Fig. 1. With Eqs. (1)–(4), one can calculate the current density \( J \) and the resistance coefficient \( r \) as a function of the tensile strain \( \varepsilon \). In this study, the \( J-V_a \) and \( r-V_a \) responses were calculated over a tensile strain range of 0%–10%. The main parameters used in the calculations are \( T=300 \) K, \( V_0=0.5 \) eV, and \( L_B=1.7 \) nm and \( L_W=5 \) nm for \( \varepsilon = 0 \). It is important to note that both the external stress-tensile strain response and the above elastic equation are assumed to be linear in this study. Such an assumption is reasonable for modest stresses. For very strong stresses, a nonlinear stress-strain response needs to be considered, and the above elastic equation needs to be modified.

It is also important to note that the in-plane dimensions of the structure are on the order of microns and, hence, their changes do not directly affect the resonant tunneling response.

Figure 2 shows the tunneling current density versus external bias voltage responses for three different tensile strains. The solid, dash, and dot curves are for a strain of \( \varepsilon = 0 \), \( \varepsilon = 5\% \), and \( \varepsilon = 10\% \), respectively. The results in Fig. 2 show that, for a DBRT structure, the tensile strain can significantly affect the resonant tunneling response of the structure. As the strain increases, the tunneling current peak shifts to higher bias voltages, and the amplitude of the current peak increases.

Figure 3 shows the resistance coefficient as a function of external bias voltage for different strains. As in Fig. 2, the solid, dash, and dot curves are for \( \varepsilon = 0 \), \( \varepsilon = 5\% \), and \( \varepsilon = 10\% \), respectively. The curves in Fig. 3 show the key result of this study, namely, a mesopiezoresistive effect. As the tensile strain increases, the resistance coefficient decreases in most of the bias voltage range. In addition, there is a peak in the resistance coefficient versus bias voltage response, and this peak shifts to higher voltages as the strain increases.

The results in Figs. 2 and 3 indicate that one can easily tune the tunneling current and resistance of a DBRT structure with an externally induced strain. Under a bias voltage of 1 V, for example, the resistance coefficient decreases from 5.33 V cm\(^2\)/A to 2.96 V cm\(^2\)/A and 1.39 V cm\(^2\)/A as the strain increases from 0% to 5% and 10%, respectively. Such an effect can be used to develop electromechanical devices and, in particular, the electromechanical transducers for nanoscale electromagnetic systems.
From the perspective of device applications, it is useful to examine the piezoresistance coefficient of the DBRT structures. For a given bias voltage, the piezoresistance coefficient can be defined as $p = \frac{\delta R}{\delta \varepsilon}$. Figure 4 shows the piezoresistance coefficient as a function of tensile strain for four different bias voltages. The strain varies from 1% to 10%. The solid circles, open circles, solid squares, and open squares are for bias voltages $V_a = 1.2$ V, $V_a = 1.3$ V, $V_a = 1.4$ V, and $V_a = 1.5$ V, respectively.

It is evident from Fig. 4 that the piezoresistance coefficient versus strain response varies significantly with the external bias voltage. For $V_a = 1.2$ V, for example, the coefficient is more or less constant in the strain range from 1% to 5% and decreases with an increase in the strain in the range from 5% to 10%. In contrast, for $V_a = 1.5$ V, the piezoresistance coefficient increases with the strain in the entire strain range. These results indicate that one can tune the resistance versus strain response with the external bias. Such tunability is important for device applications.

It is important to recall that the mesopiezoresistive effect addressed here differs from the piezoelectric effect in DBRT systems in previous studies. The effect results from the change in the barrier and well widths, rather than the creation of polarization charges. It is also important to emphasize that this effect differs from the classical piezoresistive effect. It exists only in quantum superlattice structures, and it is a quantum effect.

The mesopiezoresistive effect will have potential applications in miniature sensor devices. In fact, the effect has been used by the authors to develop miniature devices for the measurement of acceleration and the detection of acoustic signals. The sensitivity of these devices was found to be at least one order of magnitude higher than that obtained in classical piezoresistive effect-based silicon devices. Some of the experimental results based on this study was published recently in Ref. 10. A paper with more complete experimental results will be published elsewhere.

In summary, this letter reports a mesopiezoresistive effect. This effect occurs in DBRT structures and is caused by the tuning of the resonant tunneling response with the barrier and well widths. The results of the calculation show that the resistance of a DBRT structure changes significantly with external stress-induced tensile strains. The results also show that the resistance versus strain response can be tuned effectively by the external bias voltage.

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