Lateral resonant tunneling in a double-barrier field-effect transistor

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We report on electron transport measurements in a planar resonant tunneling field-effect transistor (PRESTFET) on a modulation-doped GaAs/AlGaAs heterostructure. The PRESTFET is created by defining two independently biased, 60-nm-long Schottky gates separated by 60 nm, on top of the AlGaAs layer, which presents a tunable double-barrier potential modulation to the electrons traveling from source to drain. Current measurements at 4.2 K, as a function of gate bias, with both gates connected, exhibit strong multiple negative transconductance swings at a fixed drain bias below 5 mV, providing evidence of resonant tunneling through quantized states between the two barriers. Fixing the bias on one of the gates and scanning the second, or fixing the bias on both and varying the light intensity of a light-emitting diode confirms this observation. In addition, a structure in the output conductance as a function of drain voltage at a fixed gate bias is clearly observed.

The resonant tunneling (RT) phenomenon has attracted considerable attention during the past two decades. It was first suggested and examined in grown superlattice structures, and later in grown double- and triple-barrier diodes, where a much stronger effect could be observed even at room temperature. This led to increasing interest in using the RT effect in device applications such as oscillators and logic gates. The major shortcomings inherent in vertical tunneling schemes are (1) the barrier height depends on the band-gap difference between the barrier and the well materials, and cannot be externally controlled and (2) the elastic and inelastic scattering times are relatively short in the vertical transport, since the electrons have to travel through bulk doped GaAs and undoped AlGaAs, both of them having electron mobility. This delays the response time. There have been several attempts to solve the first problem by either incorporating the tunneling structure in a field-effect or bipolar transistor, or by doping the well p type and contacting it.

To avoid these shortcomings and to maintain a long electron mean free path, we have investigated surface field-effect-induced tunneling barriers. The devices are built on top of a modulation-doped GaAs/AlGaAs heterostructure, where a two-dimensional electron gas (2DEG) is confined at the heterointerface. In this case the depletion region under the very short length Schottky gates extends into the 2DEG resulting in a tunable potential modulation. This led to the first clear observation of a lateral surface superlattice (LSSL) effect, and of mobility modulation in quasi-one-dimensional subbands, in transport measurements across and along an array of periodic barriers, respectively. In grid-gate modulation-doped field-effect transistors (MODFETs) we observed negative differential conductance, which we attributed to sequential resonant tunneling. Analogous to the evolution in grown resonant tunneling diodes, i.e., from superlattices to double and triple-barrier diodes, we have reduced the number of gates to two or three with a corresponding decrease in source-drain separation. Recently, this idea has been independently suggested by Chou et al., In this letter we present our first experimental evidence of resonant tunneling in a planar resonant tunneling field-effect transistor (PRESTFET).

The basic structure of the device is similar to a submicron MODFET except that we have two or three closely separated, independently controlled gate fingers. The layers used were modulation-doped GaAs/AlGaAs heterostructures grown by molecular beam epitaxy. The GaAs buffer layer consisted of a 10-period GaAs/AlGaAs superlattice (10 nm each) and 1 μm undoped GaAs. On top of the buffer a 7.5-nm-thick undoped AlGaAs spacer and a 40-nm-thick Si-doped (1×10^{19} cm^{-3}) AlGaAs layer were grown. The Al content was 30% in the spacer and 25% in the doped layer. Finally, a Si-doped (3×10^{19} cm^{-3}) GaAs cap layer was deposited. This resulted in a 2D electron density of 2×10^{11} cm^{-2} and a mobility of 2.8×10^6 cm^2/Vs at 4.2 K. Electron beam lithography and lift-off were used to pattern two or three 60-nm-long, 20-μm-wide Ti/Pt gates separated by a 60 nm space (i.e., 120 nm pitch). The source and drain had a separation of 1.5 μm and were defined by optical contact lithography, AuGeNi evaporation, and lift-off. In Fig. 1 a scanning electron micrograph shows a top view of the channel of a double-barrier PRESTFET. Both the gate length and the gate finger separation are very crucial to the operation of these devices. A short gate is desirable to increase the tunneling probability which results in an appreciable current density at resonance. The smaller the gate finger separation, the narrower the well in between the two barriers, and thus the further apart the quantized energy levels become. This increases the temperature range over which RT can be observed.

The devices can be operated in a regular FET mode by lowering the gate-induced barriers below the Fermi energy \( E_F \). In this case the independent control on the gates can result in a modification of the field distribution along the channel as recently suggested by Shur. Experimental results on this mode of operation will be reported elsewhere. To operate the devices in a RT mode, on the other hand, \( E_F \) has to be below the top of the barriers. The RT condition occurs whenever \( E_F \) at the source side aligns with any of the

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quantized energy levels in the well. Motion of $E_F$, relative to those levels can be achieved by changing a back gate bias or by light illumination, in which case the barrier heights remain unaltered while $E_F$ is changed, or by scanning the gate or drain bias, which shifts the position of the quantized states without affecting $E_F$ at the source side.\footnote{The specific reference is not provided.}

At room temperature the devices were normally off, as a result of the relatively low doping-thickness product of the top AlGaAs layer. The threshold voltage was around 0.05 V. The positive swing on the gate was limited to 0.6 V by the Schottky gate current leakage. The transconductance $g_m$ at this point is around 150 mS/mm, being limited by the parasitic source resistance. At 4.2 K the threshold voltage of the devices shifted up to 0.15 V and the peak $g_m$ increased to 350 mS/mm. There was no persistent photoconductivity observed, and thus the conductance of the device could be tuned by changing the intensity of a red light-emitting diode (LED). We first measured the source-drain current $I_{DS}$ as a function of gate bias $V_{GS}$, with both gates connected. The measurement was performed at 4.2 K in the dark at a drain-source bias $V_{DS}$ of 0.2 mV. The turn-on behavior of the device was very sharp due to the high low-field mobility. No gate leakage current could be detected down to the measurement limit (10 pA). In Fig. 2(a) a clear structure can be observed below threshold. On top of the exponential current rise, characteristic of the subthreshold regime (shown in dashed lines as a guide to the eye) three resonance peaks are superimposed. The largest peak-to-valley ratio is observed in the first structure, where the off-resonance tunneling component is still very small due to the relatively large difference between the top of the potential barrier and $E_F$. As $V_{GS}$ is increased, the quantized states in the well shift until $E_F$ is matched with the next state, and a second resonance is observed. Simultaneously, the decrease in energy between the top of the barrier and $E_F$ is reduced, resulting in a larger off-resonance tunneling component. In addition, due to the reduction in the confining potential barrier height, the quantized states become more closely separated making the distinction between the two tunneling components more difficult. As a result, the third structure has a reduced peak-to-valley ratio and a fourth structure (not shown in the figure) could hardly be resolved. Increasing the drain bias resulted in a gradual smearing of the peaks and valleys, and at 5 mV no structure was observable.

Two additional types of measurements were performed to complete the picture. In the first, both gate voltages were fixed at 0.12 V, a value corresponding to the first valley. Then, by changing the light intensity of a LED, the carrier density was increased, or equivalently, $E_F$ was raised with respect to the potential barrier. This measurement is shown in Fig. 2(b). Again, a strong resonance behavior was observed. The peak corresponds to the second peak in Fig. 2(a), but the difference is that in this case $E_F$ was changed with respect to the quantized states, whereas in the first measurement the opposite was done.

In the second experiment, the gate closer to the source was kept at a fixed bias $V_{GIS}$ and the second gate voltage $V_{G2S}$ was scanned. When $V_{GIS}$ was above threshold, the device resembled a single-gate MODFET and no structure was detected. On the other hand, when $V_{GIS}$ was fixed below threshold, only the tunneling component could be observed. Figure 3 shows $I_{DS}$ as a function of $V_{G2S}$ for three different values of $V_{GIS}$ below threshold. A distinct single resonance could be observed in all three cases. The position of the peak moved to lower $V_{G2S}$ for more positive $V_{GIS}$ in a systematic way. This might be an indication that we were observing the same energy state in all three cases. By applying a more positive bias on $V_{GIS}$, the position of the quantized level is shifted.
down. Thus to observe resonance through the same state, a less positive $V_{GS}$ has to be applied to shift the level up again. To quantitatively analyze the position of the peaks as a function of gate voltages, an accurate numerical calculation should be carried out.

We also looked for RT as a function of $V_{DS}$ with both gate pads connected and biased at a fixed value $V_{GS}$ below threshold. This mode of operation resembles that of a vertical RT diode, where the drain bias is used to tilt the barrier potential, thereby shifting the energy levels in the well. Resonance is expected to take place when any of those levels aligns with $E_F$ at the source side. In Fig. 4 we plot the output conductance $g_d$ as a function of $V_{DS}$ for two different values of $V_{GS}$. The measurement was performed in the dark. A deviation from the conventional gradual drop in $g_d$ is clearly observed. At $V_{GS} = 0.05 \, V$, $g_d$ is at its peak when $V_{DS} = 0 \, V$, indicating that $E_F$ was coincidently lined up with one of the quantized states. With a further increase in $V_{DS}$, a local minimum is reached at 6 mV. At 10 mV, $g_d$ shows another peak indicating a second resonance and then drops again. At $V_{GS} = 0.03 \, V$, $g_d$ is low at zero drain bias but then shows two peaks as a function of $V_{DS}$. In both cases $g_d$ increases dramatically at $V_{DS}$ beyond 20 mV due to field-assisted tunneling through, and thermionic conduction on top of the first barrier. The RT effect in this type of measurement is relatively weak and cannot be clearly seen directly in $I_{DS}$, in contrast with the previous type of measurements (Figs. 2 and 3). In a similar device structure, but with a 50% wider well, Palevski et al. could not detect any evidence for RT. They attributed that to the width of the energy distribution being wider than the separation between the top quantized levels. We believe that in our case the narrow well resulted in a larger energy level separation, and hence the effect could be detected in $g_d$. In the measurements as a function of gate voltage, on the other hand, the drain bias is kept very low and thus only electrons around $E_F$ could contribute to the RT. In other words the device operates better as a negative transconductance than as a negative output conductance device.

In summary, a double-barrier, planar resonant tunneling field-effect transistor (PRESTFET), with gate length and gate separation of 60 nm, on top of a modulation-doped GaAs/AlGaAs heterostructure was fabricated. At 4.2 K the devices show clear evidence of resonant tunneling as one or both gate voltages are scanned, or as the intensity of a LED is varied. A clear negative transconductance can be observed at low drain bias. Also evidence for resonant tunneling is detected in the output conductance as a function of source-drain bias, similar to, but much weaker than in a vertical double-barrier diode.

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![Diagram](image)

**FIG. 4.** Output conductance $g_d$ as a function of $V_{DS}$ for two different $V_{GS}$ values below threshold. Both gate pads are connected and no illumination was used.

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15. This is a first-order approximation; there is also a change in $E_F$ and in the subband separation as a function of gate bias.