Photon-Mediated Sequential Resonant Tunneling in Intense Terahertz Electric Fields

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We have measured the current-voltage (I-V) characteristic of semiconductor superlattices in the presence of intense terahertz electric fields produced by free-electron lasers. The nonlinear I-V curves exhibit new structure that we attribute to photon-mediated sequential resonant tunneling. This tunneling process consists of well to well sequential tunneling into photon sidebands induced by the terahertz electric fields.

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Quantum transport in semiconductor superlattices and multiple quantum wells in the presence of intense electric fields has attracted theoretical attention since the seminal work of Esaki and Tsu [1] some twenty years ago. While electronic states in superlattices in strong *static* electric fields are now being experimentally investigated, the rich phenomena expected in the presence of intense high frequency electric fields remain experimentally unexplored. The theoretical predictions are rich indeed. Harmonic generation, absolute negative conductivity, and self-induced transparency have emerged from a number of theoretical papers [2–6] based on a semiclassical description of superlattice transport. More recently a quantum mechanical calculation [7] using Floquet theory has shown that the miniband of "quasienergies" collapses at singular values of the ac fields. While most of the theoretical work has focused on coherent miniband transport in the presence of intense high frequency fields, with the exception of the early work of Kazarinov and Suris [8], little theoretical work has addressed the issue of sequential resonant tunneling in the presence of strong high frequency fields.

In this Letter we report on an experimental investigation of electrical transport in the sequential resonant tunneling regime of superlattices submitted to intense terahertz electric fields. We show that the far-infrared radiation introduces new photon-mediated conduction channels in these devices, a phenomenon closely akin to photon-assisted tunneling in superconducting tunnel junctions.

The lack of previous experimental work can be easily understood. The simultaneous conditions of intense and high frequency electric fields require $\omega\tau > 1$ and $eE^{\rm ac}d/\hbar\omega \gtrsim 1$. The former statement implies that the electrons should be submitted to at least one cycle of the applied ac field before scattering in a mean time τ, while the latter condition requires that the high frequency electric field of magnitude $E^{\rm ac}$, applied across a nanostructure with a width d, produces an ac voltage drop that exceeds the photon energy $\hbar\omega$. Semiconductor superlattices typically have scattering times of $\tau \approx 10^{-12}$ s and spatial period $d \approx 10$ nm. Near-infrared or higher frequency radiation can easily achieve $\omega\tau \gg 1$, but at the expense of requiring prohibitively large electric fields.

The terahertz regime achieves the condition $\omega\tau > 1$ but electric fields of the order of several kV/cm are still required. At these frequencies high power tunable sources are not commonplace but these conditions can be achieved using the free-electron lasers (FEL) at University of California–Santa Barbara. These laser systems routinely provide tunable radiation at the kilowatt power level from 120 GHz to 5 THz. A typical pulse lasts for a few μs with a repetition rate of 0.5 Hz, and can be focused down to a few millimeters diameter spot size. Further details of these lasers are given elsewhere [9].

The samples were fabricated from molecular beam epitaxy grown $GaAs/Al_{0.3}Ga_{0.7}As$ superlattices consisting of 100 periods of 33 nm wide quantum wells separated by 4 nm barriers. The structures were grown on an n^+GaAs substrate and capped by a 100 nm thick GaAs layer doped with Si to $n = 2\times10^{18}$ cm^{-3}. The superlattice itself was n doped with Si at $(2\text{–}3)\times10^{15}$ cm^{-3}. Square mesas 200 μm on a side were defined by standard photolithographic techniques and shallow AuGeNi Ohmic contacts were alloyed (45 s at 430 °C) on the mesa top as well as the substrate. Gold wires of 25 μm diameter were bonded to each contact. The experiments were performed over a temperature range 2–300 K, with the samples mounted in a temperature controlled flow-type cryostat with Mylar and Z-cut crystal quartz windows.

The radiation from the FEL was coupled into the sample by using the gold bonding wire as an antenna (Fig. 1). The angle of incidence and polarization direction with respect to the antenna were adjusted for each frequency to maximize the coupling efficiency. The wavelength of the radiation is of the order of several hundred microns, comparable to the mesa dimensions, but much larger

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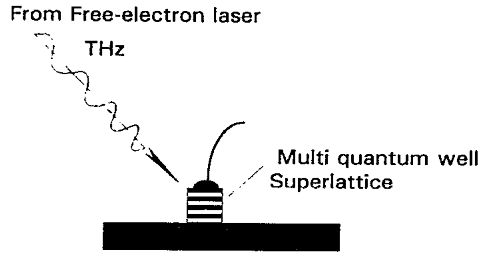

FIG. 1. A multiple quantum well superlattice is irradiated by radiation from the free-electron laser. The bonded wire acts as an electrical contact and an antenna for the THz radiation.

than the superlattice thickness. The contact metallization effectively short circuits the electric field parallel to the layers, leaving only the normal component. Although we can measure the power incident on the sample, we have no quantitative measurement of the coupling strength and do not have an accurate value of the absolute magnitude of the ac electric fields *in* the sample. Typical maximum power levels are of the order of several kilowatts at 600 GHz and focused to a few square mm will generate free space electric fields of the order of several kV/cm. We may assume that the terahertz electric field in the superlattice is of this order of magnitude. However, an accurate value of the magnitude of the ac electric field is not needed in what follows.

Figure 2 shows the dc current-voltage, I-V, characteristics at 75 K, without and with terahertz radiation at three different frequencies. The static characteristic, $E^{ac}=0$, shows the series of steps in current associated with sequential resonant tunneling in a superlattice [10]. At low biases ($V \leq 100$ mV) the current through the superlattice is controlled by ground state to ground state, well to well tunneling. At the maximum current that can be supported by this channel the Ohmic transport saturates and subsequent increases in the applied voltage will lead to the formation of a high field domain where the electronic conduction occurs via tunneling from the ground state in one well to the first excited state in the neighboring well, followed by an intrawell relaxation of energy from the excited to the ground state. The current stays limited by the ground state to ground state tunneling in the low field region. As the bias increases the high field domain expands until it takes over the whole sample. At this point ($V \approx 1.2$ V) the voltage across the superlattice is again uniform and electronic conduction is through the tunneling-relaxation mechanism. With increasing bias, this mechanism also saturates and similar processes will occur involving higher quantum well states and leading to additional steps in the I-V characteristic.

Although experiments were performed from 2 to 300 K, the best results were obtained for $T \leq 100$ K. At higher temperatures the static I-V characteristic is somewhat washed out. Below 100 K the static I-V did not change but at substantially lower temperatures weakly non-Ohmic junctions rectify the THz radiation producing unwanted background signals.

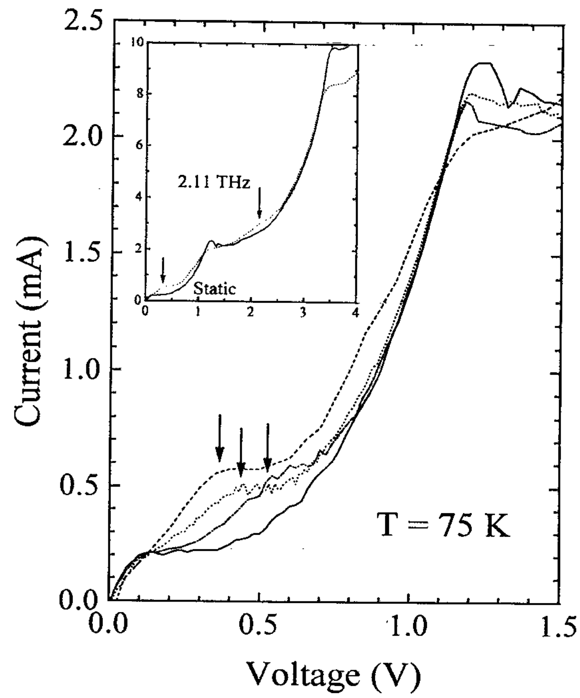

FIG. 2. Current-voltage characteristics at 75 K measured without (solid line) and with the sample in the presence of radiation at 1.50 THz (dash-dotted line), 1.83 THz (dotted line) and 2.11 THz (dashed line). The inset is an extended view of the static and 2.11 THz I-V curves showing the additional structure around 2.1 V. Arrows point to features assigned to new photon-assisted channels for sequential resonant tunneling.

Under intense terahertz excitation new steps and plateaus appear in the I-V curves. Figure 2 shows examples for the three different frequencies. The position in bias of the new steps is a function of frequency, with the onset of the new plateaus moving to lower voltages as the frequency increases. We note also a weak dependence of the onset of the plateaus on the intensity of the laser. These results do not change significantly with temperature as long as the temperature is low enough ($T \leq 100$ K) for the conduction to be dominated by quantum tunneling.

Figure 3 shows the frequency dependence of the new structure induced in the I-V characteristic by the terahertz radiation. The voltage position of the onset of a new plateau was defined by the knee and measured by the position of the minimum in $\partial^2 I/\partial V^2$. The total dc voltage applied to the sample has been divided by 100, the number of quantum wells and barriers. For each frequency we plot the data obtained from measurements at different laser powers. The solid lines in the figure are best straight line fits.

There are two striking features in Fig. 3. First, the data lie along lines that have slopes $\Delta V/\Delta f = -h/e$, to within the experimental error. Second, the $\omega=0$ intercepts of these lines, 11.8 meV and 30.6 meV, correspond

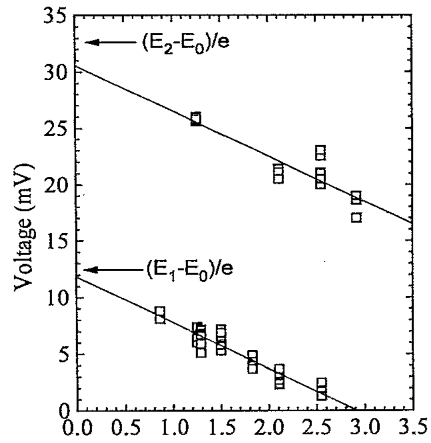

FIG. 3. The voltage positions of the onsets of the new ac-induced plateaus in the I-V characteristic of the superlattice, as a function of the frequency. The voltages are the voltage drops across a single period of the superlattice assuming a uniform dc electric field. Arrows point to the voltage offset between the ground state and first two excited states in the quantum wells.

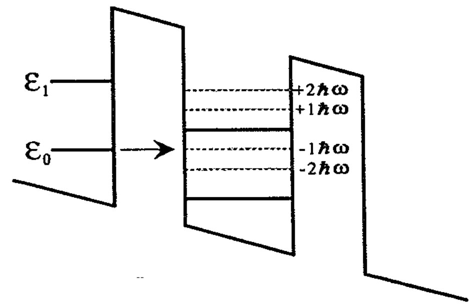

FIG. 4. Sequential tunneling in the presence of an ac field can be viewed as tunneling to photo sidebands of a state in the neighboring well.

closely to the calculated energy separations between the ground state, $\mathscr{E}_0$, and the first, $\mathscr{E}_1$, and second, $\mathscr{E}_2$, excited states, respectively. Using a simple envelope function approximation in the absence of a dc electric field, we obtain $\mathscr{E}_1-\mathscr{E}_0=12.4$ meV and $\mathscr{E}_2-\mathscr{E}_0=32.7$ meV.

The results shown in Fig. 3 strongly suggest that the new structure induced in the I-V characteristic by the terahertz radiation is due to photon-mediated tunneling and that the dc voltage is dropped uniformly across the sample, at these bias points, in the presence of the intense terahertz radiation. We discuss this further below. The far-infrared electric field opens a new conduction channel, in which an electron can tunnel from the ground state in one quantum well to an excited state $\mathscr{E}_n$ in the neighboring well with the absorption of a photon. The electron then releases the excess energy $eV=(\mathscr{E}_n-\mathscr{E}_0)$ in an intrawell transition to the ground state and a new photon-mediated tunneling process to the next quantum well follows.

The new steps in the I-V curves occur at voltage biases where the static conditions necessitated high electric field domains. These domains will be altered only when the new conduction channels are strong enough to dominate the transport. Our model implies that the terahertz fields are sufficiently strong to make photon-mediated tunneling a significant mechanism of electronic conduction, at least around the dc biases where the new structure in the I-V curve is observed. This is consistent with the significant change in current induced by the FEL at these biases. We conclude from the data that the terahertz radiation forces a nearly uniform distribution of the applied dc voltage at these positions in bias. It is possible that some of the power dependency of the data points in Fig. 3 is due to residual field inhomogeneities. Generally, the new steps in the I-V curve appear at slightly higher dc bias as the intensity of the laser field is increased. Since the coupling of the radiation is not controlled, we cannot know the relative THz electric fields at different frequencies, but we can assume that the electric field at a given frequency scales with the square root of the incident power. These issues will be addressed in future work.

The photon-mediated tunneling process can be understood in terms of photon sidebands. Following Tien and Gordon [11], we consider only the tunneling between two of the coupled quantum wells. One well can be thought to be fixed while its neighbor is oscillating up and down in a potential $V(t)=edE^{ac}\cos\omega t$. The resulting electronic wave function in the time-modulated quantum well will be

$$\Psi(\mathbf{r},t)=\Psi_0(\mathbf{r},t)\sum_{n=-\infty}^{\infty}J_n(edE^{ac}/\hbar\omega)\exp(-in\omega t),$$

where $\Psi_0(\mathbf{r},t)$ is the unperturbed eigenfunction (without the oscillating field) and $J_n(z)$ are the Bessel functions of the first kind. The effective density of states is distributed over sidebands separated by multiphoton energies $n\hbar\omega$. Therefore, in the presence of the ac electric field, photon-mediated tunneling channels are predicted to appear at energies separated from the final state by $\pm n\hbar\omega$. The contribution of the photon-assisted processes to the transport becomes significant when the argument of the Bessel functions, $eE^{ac}d/\hbar\omega$, is of the order of unity.

The concept of photon sidebands provides a clear view of the origin of the terahertz-induced structure in the I-V curve. The new steps are due to processes similar to the ones that produce the plateaus in the static characteristic, except that the tunneling is from the ground state in one well to a photon sideband in the neighboring well, as shown schematically in Fig. 4.

Another important consequence which emerges from the photon sidebands picture is that the photon-mediated tunneling rates are proportional to J_n^2. As a result, one should expect the change in current due to the photon-mediated tunneling to depend on the intensity of the terahertz radiation. The observed change in current does show a dependence on the laser power. However, since clear new steps occur only at the highest powers, a clear J_1^2 dependence is not seen. Further work to increase and quantify the terahertz radiation coupling to the superlattice is in progress.

We also note that we see only photon-mediated processes involving the absorption of a photon. No stimulated transitions to lower states in the collecting well (emission of a photon) are seen. In particular no photon stimulated emission is seen between E_0 and E_0 in neighboring wells. We have no explanation for this.

In conclusion, we report the first experimental evidence of a photon-mediated sequential tunneling process in a semiconductor structure. This tunneling mechanism consists of well to well sequential resonant tunneling into photon sidebands in a semiconductor superlattice submitted to intense electric fields at terahertz frequencies. These experiments open the way for the realization of proposed [12,13] measurements of tunneling times using time-modulated barriers and for the verification of the several effects, such as Bloch oscillations, self-induced transparency, and absolute negative conductivity, which are predicted to occur in a spatially periodic structure submitted to a strong modulation in time.

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