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EXPERIMENTAL INVESTIGATIONS OF THE QUANTUM PHOTOVOLTAIC EFFECT IN InAs-GaSb SEMICONDUCTOR SUPERLATTICES

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Nous rendons compte de l'observation d'un effet photovoltaïque d'origine quantique dans des superréseaux semiconducteurs InAs-GaSb. Les résultats sont conformes aux prédictions théoriques, à l'exception du signe de l'effet qui met en évidence une dépopulation de la couche de surface.

We report the observation of the quantum photovoltaic effect in InAs-GaSb semiconductor superlattices. The results are consistent with the theoretical predictions, except for the voltage sign which evidences a depopulation of the surface layer.

Recently, Brum et al. \(^1\) predicted the existence of a new photovoltaic effect in type-II superlattices (SL). Their idea, based on quantum mechanics, is that the localization of the electrons and holes wavefunctions within different layers makes each period of the SL act as a quantum capacitor, its positive (negative) electrode being the hole (electron) confining layer. The local polarizations \(\delta V\) arising within each capacitor add and create a macroscopic potential difference \(\Delta V\) across the SL. If only the ground valence and conduction subbands come into play the potential difference \(\Delta V\) across the SL simply reads:

\[
\Delta V = N \delta V \quad \text{with} \quad \delta V = n_s e (\langle z_e \rangle - \langle z_h \rangle) / \varepsilon \varepsilon_0
\]

where \(N\) is the number of periods, \(n_s\) the areal density of injected carriers, \(\varepsilon\) the relative dielectric constant and \(\langle z_e \rangle, \langle z_h \rangle\) the mean z-position of the electron (hole) ground state.

In type-II SLs, because of the symmetry of ground state wavefunctions of both electrons and holes, \(\langle z_e \rangle\) and \(\langle z_h \rangle\) are located at the center of host layers, and the electron-hole mean separation is simply \(\Delta z = d(P_e + P_h - 1)/2\), where \(d\) is the SL period and \(P_e\) and \(P_h\) the probabilities for the carriers to be in their respective confining layer\(^2\).

However, as the conductance of the SL along the growth axis is nonzero, under constant charge injection the system will return to thermodynamical equilibrium via charge transport (with time
constant RC) to both ends of the SL, leaving no potential difference across the structure. Assuming that the carrier thermalization is instantaneous, the photovoltage $\Delta V$ and the carrier density $n$ are governed by the following rate equations:

$$\frac{dn}{dt} = G(t) - n/\tau \quad \text{and} \quad \frac{\partial \Delta V}{\partial t} = n_{eq} \frac{\partial n}{\partial t} - \Delta V/RC$$

(2)

where $\tau$ is the carrier recombination time, $RC$ the transport time across the whole structure, and $G$ the carrier generation rate, which is essentially proportional to the excitation intensity.

For $G(t) = G_0 \Theta(t)$ (a step function with carrier density saturation value $n_s = G_0 \tau$), this yields:

$$\Delta V(t) = G_0 \tau \frac{\Delta z}{\varepsilon \varepsilon_0 RC/(RC-\tau)} \left(e^{-t/\tau} - e^{-t/RC}\right) \Theta(t)$$

(3)

In the case $RC \ll \tau$, the photovoltage peak occurs at time $t = \tau \log(RC/\tau)$, then exponentially relaxes with decay time $RC$. On the other hand, if $RC \ll \tau$, the conductivity of the structure dominates and essentially no voltage should appear.

Our samples consist of InAs-GaSb SLs with different layer thicknesses and substrates. We evaporated a ring-shaped gold contact of diameter 200 $\mu$m and thickness 0.2 $\mu$m upon the free SL surface. The substrate side was contacted with silver lacquer. Only one of our samples presents a RC constant large enough to measure full-size signals, as predicted by Eq. (3). This is a fifty periods SL with 30 $\AA$ InAs and 50 $\AA$ GaSb layers grown on a conducting GaAs $n^+$ substrate. We processed two devices (I and II) on this wafer.

We use a cavity-dumped Kr+ laser that produces 6.5 W peak power, 20 ns-long light pulses, focused within a 100 $\mu$m spot. The photovoltaic signal was displayed on a fast oscilloscope or analysed through a boxcar integrator with a time resolution of 5 ns. These excitation conditions are known to produce in equivalent samples an areal density of injected carriers in the range of $10^{11}$ cm$^{-2}$. Besides, from the evaluation of the ground state envelope functions, $P_e = 0.7$ and $P_h = 1$. With these parameters, Eq. (3) yields $\Delta V = 180$ mV, which compares favorably with photovoltage peak values of $\approx 50$ mV measured on both devices. Up to this maximum, the photovoltage increases linearly with the excitation power. The time response of the photovoltage is shown in Fig. 1 together with the shape of the exciting pulse. The voltage pulse decay time is significantly larger than that of the excitation (28 ns and 23 ns with devices I and II, respectively), which, according to Eq. (2), indicates a recombination time $\tau$ in the range 5-9 ns. This is a plausible value given the weak overlap of the electron and hole wavefunctions in type-II SLs. However, the device dependence of this determination has to be elucidated, and future experiments with picosecond excitation should give more precise determination of $\tau$.

When we use long excitation pulses (10 $\mu$s, i.e. much longer than RC), the signal consists of two pulses of the form predicted by Eq. (2), as shown in Fig. 2. With device I (II) the front pulse relaxes to zero with a decay time of 1020 ns (560 ns). After the excitation cut-off, the carriers recombine rapidly in the SL, leaving the charges accumulated at the terminating planes: this gives rise
to an end pulse of opposite sign, which then relaxes to zero with a decay time of 1200 ns (I) or 740 ns (II). This signal profile is characteristic of this new photovoltaic effect which has a quantum origin, but is blurred out under DC conditions through a classical transport mechanism. The observed peak voltage value is nearly 1 mV under 100 mW excitation, which corresponds to an efficiency of $10^{-2}$ V/W, similar to that observed for the 20 ns-pulse excitation. The longer decay time of the end pulse is due to the resistivity increase (here $=25\%$) due to the decrease in carrier density as the exciting light is cut off.

The measurements reported so far were made at $T=12$ K. Figure 3 displays the temperature dependence of the photovoltage in the 20 ns-pulse excitation regime. As expected from its quantum origin, the signal is fairly constant over a large temperature range; then it drops by a factor of $=3$ around $T=130$ K, probably as a result of the thermal activation of optical phonons, which leads to a significant resistivity decrease; then, following Eq. (3), this SL resistivity fall lessens the measured voltage.

According to Ref. 1, the sign of the photovoltage depends only on the nature of the SL surface layer. In this sample, the top layer is InAs, and the photovoltage should be negative, the opposite of our observations. The explanation of this surprising discrepancy is likely to be the following: due to the large vacuum barrier height, the surface InAs layer forms a special quantum well presenting a ground energy level much higher than the SL ground state, and therefore much higher than the quasi-Fermi level. Thus, the last electrically active layer is the underlying GaSb layer, which accounts for the sign reversal of the quantum photovoltage. Calculations of the energy spectrum in the finite SL do support this explanation.

In conclusion, we have demonstrated the existence of the Quantum Photovoltaic Effect, as predicted in Ref. 1, in a InAs-GaSb semiconductor SL. This original effect could allow direct measurements of the electron-hole recombination time in type-II SLs, as well as be used for IR detectors of tailored energy threshold.

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References:
3 P. Voisin and J. Bleuse, unpublished
Fig. 1.
Photovoltage time response compared with the light pulse profile under 20 ns-long excitation for device I.

Fig. 2.
Same as Fig. 1 under 10 μs-long excitation.

Fig. 3.
Peak photovoltage versus temperature T under 20 ns-long excitation for device I (the dashed line is a guide to the eye).