PHASE-CONTROLLED PHOTOCURRENTS IN SEMICONDUCTORS

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Abstract:

We show that one can optically control the photoresponse of semiconductor devices by the phase of the EM incident radiation. This can be achieved by interfering two phase-locked quantum pathways, both projecting the same initial bound state to the same energy level in the continuum. An experimental study on quantum well infrared photodetectors is presented.

We experimentally show that all-optical control of the photoresponse of GaAlAs quantum well detector can be achieved using quantum interference in the continuum between free electronic waves which are excited by two different pathways. Initially, this effect of interference between different quantum pathways was first demonstrated in Xenon photo-ionization experiments\(^1,2\). Taking profit of the quantum interference phenomena between optical transitions in rubidium, Yin et al.\(^3\) could control the angular distribution of photoelectrons. These experiments prove that, in some cases, the phase of a quantum state is as important a variable as frequency. The importance of phase is equally true in single atoms or in semiconductors. For instance, it was recently observed that quantum beats in coupled quantum wells excited with two consecutive laser pulses depended on the relative phase difference between the two pulses\(^4\).

The idea to extend the general concept of phase-controlled photo-ionization to semiconductor devices was theoretically discussed by Kurizki et al.\(^5\). Here, we experimentally show that this concept of coherent control is not confined to atomic quantum systems; it can also be applied to more complicated materials like solid-state devices. Indeed, we report here all-optical modulation of photocurrent, including its sign, in standard mid-infrared GaAs/GaAlAs quantum well (QW) detectors by controlling the quantum interference between two degenerate states in the continuum. Two independent quantum paths were used to “populate” the two quantum pathways from the ground state to the energy level \(\mid E, A\rangle\) in the continuum.

\begin{center}
\textbf{Fig. 1} The two quantum pathways from the ground state to the energy level \(\mid E, S\rangle\) in the continuum.
\end{center}
these continuum states (see Fig. 1). The two paths were (1) a two-photon non-resonant electron intersubband transitions[6] at 10.6μm to excite electrons from the ground level to the symmetric state |E,S> and (2) a linear absorption at 5.3μm to excite electrons to the antisymmetric wave |E,A>. These simultaneously excited states interfere and, depending on the phase (φ_{10.6}, φ_{5.3}) and the intensity of each beam, the electron can be partially or completely described by a positive or negative progressive wave. One can estimate the current density \( j \) resulting from the interference:

\[
 j = \frac{q}{L} \frac{2\pi}{h} \mu^{(2)} \mu^{(1)} E^2_\omega E^2_{2\omega} D'_{10}(E) \mu \frac{\hbar k \sin(2\phi_{10.6} - \phi_{5.3})}{m' \sqrt{1 + \left[(m' k/m k' - m k/m' k)/2\right]^2 \sin^2(kd)}}
\]

where \( m \) and \( m' \) stand for the effective mass in the well and the barrier; \( k, k' \) represent the longitudinal free electron momentum in the well and the barrier with an energy \( E \); \( \mu^{(2)} \) and \( \mu^{(1)} \) are the dipole moments of the linear and quadratic absorption; \( E_\omega \) and \( E_{2\omega} \) are the amplitude of the fundamental and the second harmonic field; \( D'_{10} \) is the one-dimensional density of state; \( L \) is the superperiod of the structure; \( n_\omega \) is the electron concentration in the QWs; \( \tau \) is the free electron collision relaxation time (\( = 100 \mu s \)). Practically, the sin function in this expression implies that by adjusting the phase difference \( \Delta \phi = 2 \phi_{10.6} - \phi_{5.3} \) the electron can be directed to the right or to the left of the quantum well. The expression within the square root describes the energy dependence of the dipole moment between the symmetric and antisymmetric states, and therefore the strength of interference.

In our experiment, the 5.3μm photons come from the second harmonic of a 10.6μm CO\(_2\) hybrid TEA laser. The relative phase of the co-linear 5.3 and 10.6μm beams is varied by passing the two beams through a 1" NaCl crystal mounted on a rotating stage (see Fig. 2). After amplification, the signal are recorded on a digital scope and gated integrators. The Fig. 3 shows a scan of the photoresponse of a detector when one rotates the salt crystal. The sign of the photocurrent can be inverted by a rotation of the salt crystal of few tenth of degrees. From the period of the fringes the deduced dispersion \( n_{2\omega} - n_\omega \) of our NaCl window is 2.54 × 10\(^{-2}\), which is 7% lower than the data book value. As described above by Eq.1, the amplitude of oscillations varies linearly with the 10.6μm intensity. We checked that this signal is strongly sensitive on the polarization, which is expected for intersubband excitation in n-doped GaAs/GaAlAs QWs.

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**Fig. 2** Experimental setup of the coherent-control experiments