Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 741-744

S-A-7

Invited

Ultrafast Optoelectronic Processes in Quantum Well Structures

Masamichi YAMANISHI

Department of Physical Electronics,
Hiroshima University, Shitami, Saijyocho,
Higashihiroshima, 724, Japan

Basic physics behind virtual excitation of electrons by off-resonant light is illustrated pointing out a clear correspondence of the virtual excitation with coherent electron transport. Experimental result on ultrafast response evaluation of the virtual excitation in a GaAs/AlGaAs quantum well structure is demonstrated. Extremely fast modulation schemes for quantum interference due to virtual excitation in semiconductor mesoscopic structures are described together with possible application of these modulation schemes to ultrahigh speed optoelectronic devices.

1. INTRODUCTION

Ultrafast optical processes based on virtual excitations of electrons in quantum well structures have been attracting a great deal of attention from fundamental and practical points of view. For instance, an ultrafast dynamical blue shift (ac Stark effect) accompanied by a strong bleaching in AlGaAs quantum-well (QW) structures has been discovered1)2) and interpreted in terms of a dressed-exciton model1)3) in which a coherent and direct nonlinear interaction of virtual excitons with photons plays an essential role. Also, a new modulation scheme, named virtual charge-induced optical nonlinearities (VCON), in which polarized virtual pairs in a dc-biased QW modulate internal field has been proposed4)5). The switching speed of the optical processes based on these mechanisms is expected to be extremely fast, and to be unlimited by $C{\bullet}R$ time constant and recombination life time. Basically, the ultrafast switching capability results from virtual excitation of electrons which is coherent process in time domain. On the other hand, there has been a significant interest for quantum transport of electrons in mesoscopic structures6) which are based on coherent wave nature of electrons in spatial domain. Apparently, there exists a clear correspondence of the virtual excitation with the quantum transport of electron waves.

In this paper, I shall describe basic physics behind the virtual excitation with some emphasis on the correspondence between them and then demonstrate experimental data on time-resolved autocorrelation photocurrent (PC) signals in a p-i-n diode exhibiting AlGaAs QWs showing the ultrafast switching capability of the virtual excitation. Finally, extremely fast modulation schemes for quantum interference current due to virtual excitation in semiconductor mesoscopic structures will be illustrated, pointing out their possible application to ultrafast optoelectronic devices.

2. BASIC CONCEPT OF VIRTUAL EXCITATION7)8)

There exist many quantum states involving excitonic and subband states in actual QW structures. Nevertheless, in order to focus on the essential physics, we postulate a simple two-level system with an energy separation between quantum states of $\hbar(\omega_2-\omega_1)$ and interacting with a classical radiation field, $E_p(t)\cos(\omega t)$. The state function of an electron, virtually excited by the off-resonant radiation field is described by a linear superposition of $\phi_1(\mathbf{r})$ and $\phi_2(\mathbf{r})$ which are eigenfunctions of the unperturbed Hamiltonian H_0,

$$\varphi(\mathbf{r},t) = a_1(t)\phi_1(\mathbf{r})e^{-i\omega_1 t} + a_2(t)\phi_2(\mathbf{r})e^{-i\omega_2 t} \quad . \qquad (1)$$

In the low radiation power regime, the amplitude functions $a_1(t)$ and $a_2(t)$ at stationary condition are given by

$$\left.\begin{array}{l} a_2(t) = -(\Omega/\Delta)e^{-i\Delta t} \\ |a_1(t)|^2 = 1 - |a_2(t)|^2 \end{array}\right\}, \qquad (2)$$

for an adiabatic switch-ON of the radiation field, where $\Omega(t)=\mu E_p/2\hbar$ and $\Delta=(\omega_2-\omega_1)-\omega$ are the Rabi frequency and the detuning frequency, respectively. Equation (1) combined with Eq.(2) indicates that the virtual excitation is a coherent process in time domain.

If two kinds of radiation fields with different frequencies ω and ω' and different amplitudes, E_p and E'_p interact with the two-level system, the amplitude $a_2(t)$ in Eq.(1), representing the virtual electron population at the upper level is given by,

$$a_2(t) = -\left\{(\Omega/\Delta)e^{-i\Delta t} + (\Omega'/\Delta')e^{-i\Delta' t}\right\} , \qquad (3)$$

where $\Omega' = \mu E'_p / 2\hbar$ and $\Delta' = (\omega_2 - \omega_1) - \omega'$.

Thus, the upper level population $|a_2(t)|^2$ should show a beating in time domain, i.e.,

$$|a_2(t)|^2 = (\Omega/\Delta)^2 + (\Omega'/\Delta')^2 + 2(\Omega/\Delta)(\Omega'/\Delta')\cos\{(\omega - \omega')t\} . \qquad (4)$$

The beating in the virtual population exactly corresponds to the quantum interference phenomenon in spatial domain regarding coherent electron-wave propagation.

3. ULTRAFAST RESPONSE EVALUATION OF VIRTUAL EXCITATION BY OFF-RESONANT OPTICAL PULSE MIXING9)

In this section, experimental result on the ultrafast response evaluation of the virtual excitation through the observation of photocurrents in GaAs/AlGaAs QW structures will be demonstrated with an optical pulse mixing technique.

Using the pulse mixing technique, which relies on the inherent nonlinear dependence of carrier population on pump power, we observed PC signals in p-i-n diodes including GaAs(L_z=120Å or 150Å)/AlGaAs multiple QW (MQW) structures at T=120K. The experimental set up is shown in Fig.1. We used a dye laser emitting short pulses with durations, 0.75~3ps and a repetition rate of 3.8MHz at wavelengths of 820~850nm. For the measurement each of the optical pulse sequences was chopped at a different frequency f_1=163Hz or f_2=230Hz and the PC flowing through the diode was evaluated with the lock-in amplifier at the sum frequency, f_1+f_2=393Hz to selectively detect nonlinear mixing components of the PC signals.

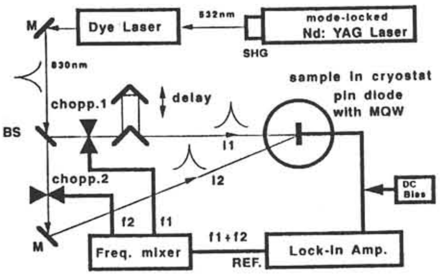

Fig.1 Experimental arrangement for the measurement of the photocurrent mixing signals in GaAs/AlGaAs MQW-diodes.9)

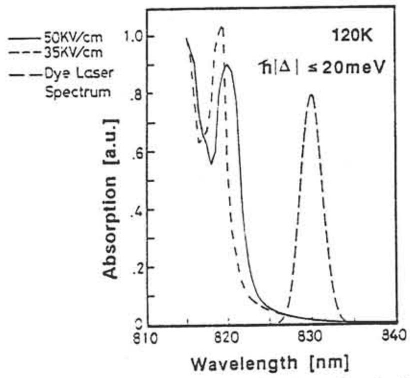

Fig.2 Absorption spectra of the GaAs/AlGaAs MQW with a thickness of L_z=120Å, biased by electric fields of 50kV/cm (solid line) and 35kV/cm (dotted line) at T=120K.9) The spectrum of the pulsed pump light (dashed line) is also shown in the figure.

Figure 2 shows the absorption spectra of the GaAs(L_z=120Å)/AlGaAs MQW structure for weak light, in the presence of electric fields, 35kV/cm and 50kV/cm, together with the spectrum of the pump pulse. In our experiment, we were concerned with a relatively small detuning energy, $\hbar\Delta \leq$20meV resulting in a considerable competition between the virtual and real excitons. It turns out that such competition between them gave us time-resolved autocorrelation signals in subpicosecond regime in spite of the fact that we were detecting PC signals resulting from the real carriers. Figure 3 shows the autocorrelation PC signals evaluated at the sum frequency as a function of time delay between the two optical pulses with a photon energy below the exciton gap, $\hbar\Delta$=20meV and with a pump power density of 20MW/cm^2. A very sharp spike appears in the output signals when the two optical pulses partially overlap each other in time domain. The observed spike almost reproduces the shape of the optical pulses with a duration of 750fs. However, strictly speaking, the spike in the autocorrelation signal is slightly wider than the pump pulses, as shown in Fig.4. The optical pulse mixing technique mentioned above was originally developed to evaluate speed of response of high speed photodetectors10)11). Actually, they have seen short autocorrelation signals in picosecond regime with their high speed detectors. The picosecond signals came out from high speed photo-responses of the detectors. On the other hand, we can never expect such a high speed response of the PC for the present MQW diodes since the carriers exited in each QW have to pass through many barrier layers to result in the PC signals. The transit times of the electrons and holes across the MQW structures may be quite long, several hundreds picoseconds12). Therefore, the observed short spikes can not be

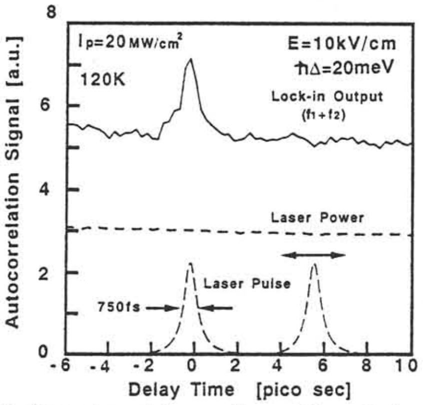

Fig.3 Experimental result on the photocurrent mixing signal vs. time delay between the two optical pulses with the duration of 750fs for a GaAs/AlGaAs (L_z=120Å) MQW-diode, biased by an electric field of 10kV/cm and off-resonantly pumped with a detuning energy of 20meV and a power density of 20MW/cm^2 at T=120K9). The pulse shapes of the pump light are also shown by the dashed line.

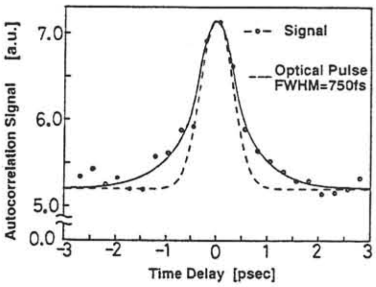

Fig.4 Enlarged plots of the photocurrent signals (circles) shown in Fig.3 around zero time delay, compared with the shape of pump pulse (dashed line)9).

ascribed to nonlinearity involved in the carrier transit processes. Nevertheless, we have seen extremely short spikes in autocorrelation signals of PC as shown in Figs.3 and 4.

As origins of the spikes in the output signals, there exist two kinds of possibilities : (1) two photon absorption13) and (2) absorption bleaching by virtual excitation, due to phase space filling or pump-induced blue shift of the exciton gap caused by the ac Stark effect1)2) and/or the VCON process4)5). We confirmed that the PC signal was saturated with the increasing pump power and that the autocorrelation signal for two optical pulse sequences chopped at a common frequency, f_1 or f_2, which was evaluated at the common frequency showed a shallow dip when the two pulses partially overlap each other in time domain. As a result, the former possibility can be excluded from the generation mechanism for the mixing signals. From a fair correspondence of our experimental data with theoretical results based on Bloch equation for a simple two-level system taking into account of the phase space filling and the pump-induced blue shift, we conclude that the observed short spikes in the autocorrelation signals indicate the ultrafast response of the virtual excitation as a precursor of the real excitation, and that the slight widening of the autocorrelation signals shown in Fig.4, compared with the shapes of the pump pulses is caused by non-adiabatic response of the virtual excitation, approximately $6/\Delta$ ~150fsec for a detuning energy of 20meV, which is ultimate limit of the response time of the virtual excitation.

4. ULTRAFAST SWITCHING OF QUANTUM INTERFERENCE BY VIRTUAL EXCITATION

In a dc-biased or built-in asymmetric QW a net charge polarization would be induced by virtual excitations caused by an off-resonant pump light with a photon energy $\hbar\omega$ far below the fundamental excitonic gap of the QW, as shown in Fig.5. The induced virtual charge polarizations may partially screen the original field E_0, resulting in a decrease E_s of the internal electric field4)5). The virtual population can follow the pump pulse with an intrinsic response time, ~$6/\Delta$. In addition, the field cancellation directly results from the internal charge inside the QW. Therefore, the modulation speed of the internal field is not limited by the recombination life time and $C{\bullet}R$ time constant.

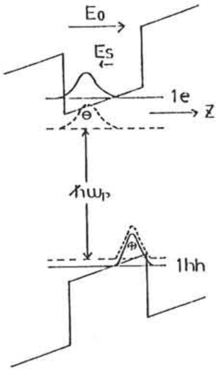

Fig.5 Energy band diagram of QW biased by a dc electric field E_0 and pumped by an off-resonant light4).

One of the most striking features of this modulation scheme is a possibility of generation of ultrafast voltage pulses in a diode exhibiting MQW structure5). A possibility of ultrafast electro-static control of quantum interference currents through the voltage pulse generation has been discussed7). In the device structure shown in Fig.6 the quantum interference current flowing in the branches A and B could be controlled through the modulation of voltage drop V_{AB} between the branches, due to the virtual charge polarizations in the MQW structure inside the branches. The thickness L_{ZQ} of the branches should be smaller than that

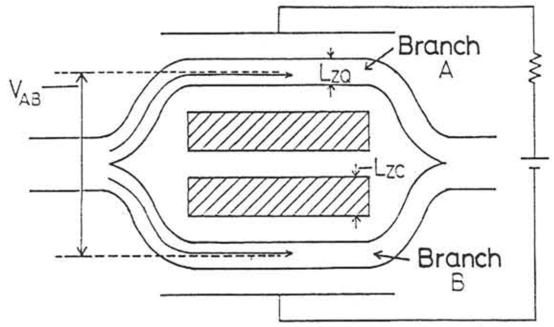

Fig.6 Cross sectional view of the proposed device for the ultrafast control of quantum interference currents7).

L_{ZC} of the MQW to selectively excite virtual pairs in the MQW. The screening field E_s may induce a voltage pulse between the branches A and B in Fig.6 given by

$$\Delta V_{AB} = (N \bullet E_s \bullet L_{ZC})$$

where N is the period of the multiple quantum wells. In general, the modulation depth ΔV_{AB} of gate voltage required for 100% modulation of quantum interference currents is fairly small for instance6),

$$\Delta V = \frac{h}{2e}\left(\frac{v}{L}\right) = \frac{h}{2e}\left(\frac{1}{\tau_t}\right) \sim 2\text{mV}$$

for a channel length, L=2000Å and an average electron velocity (Fermi-velocity), v=1.86x10^7cm/sec, i.e., a transit time, τ_t~1.1psec. Such a small modulation of the voltage would be realized by a pump power density, ~25MW/cm^2 and a detuning energy of 15meV in the device with 10 period graded gap quantum wells. Also, it is extremely important that the switching of the internal voltage due to virtual charge polarizations is expected to be free from $C \bullet R$ time constant, resulting in a fairly short switching time, ~1psec and, consequently, a small power delay product of the device, 250 femtojoule/μm^2. Many devices stacked on a single chip could be cascade-driven by a single pump pulse because the virtual process is, at least in principle, loss free and because the virtual charges do not interact with dissipative systems such as external circuits but with coherent electron waves resulting in the modulation of the phase difference between the electron waves14). This is, in general, an important advantage of this kind of modulation scheme for the quantum interference based on virtual excitations.

Another possibility of modulation of quantum interference based on exchange interaction between virtual excitons and coherent electron waves in quantum wire structures has been recently discussed15). Furthermore, Shimizu and his coworkers16)17) have pointed out a possibility of completely absorption-free photo detection by making use of level shifts resulting from ac Stark effect associated with intersubband virtual excitations. Also, it has been pointed out by Shimizu18) that the advantage of the loss-free photodetection can be further elaborated to realize a new scheme for quantum nondemolition measurement of photon number.

The modulation schemes for electron quantum interference discussed in this paper may open up new opportunities in ultrafast optoelectronics in the future. Also, such schemes may present us powerful tools for characterization of dynamics of the quantum interference phenomena, which is completely undeveloped field.

5. REFERENCES

1) A.Mysyrowicz, D.Hulin, A.Antonetti, A.Migus, T.Masselink and H.Horkoc; Phys. Rev. Lett. 56(1986) 2748.

2) A Von Lehmen, D.S.Chemla, J.E.Zucker and J.P.Heritage; Optics Lett. 11(1986) 609.

3) S.Schmitt-Rink D.S.Chemla; Phys. Rev. Lett. 57(1986) 2752.

4) M.Yamanishi; Phys. Rev. Lett. 59(1987) 1014.

5) D.S.Chemla, D.A.B.Miller and S.Schmit-Rink; Phys. Rev. Lett. 59(1987) 1018.

6) For example, S.Datta, M.R.Melloch, S.Bandyopadhyay and M.S.Lundstorm; Appl. Phys. Lett. 48(1986) 487.

7) M.Yamanishi, M.Kurosaki, Y.Osaka and S.Datta; Proc. 6th Int. Conf. Ultrafast Phenomena, Kyoto July, 1988 (Spronger-Verlag) p.334.

8) M.Yamanishi; J. Superlattices and Microstructures 6(1989) 403.

9) Y.Sakata, M.Yamanishi, Y.Yamaoka, Y.Kan and I.Suemune; presented at CLEO/IQEC '90, Anaheim, May 21-25, 1990, Paper No. JTuC5.

10) T.F.Carruthers and J.F.Weller; Appl. Phys. Lett. 48(1986) 460.

11) R.Loepfe, A.Schaelin, H.Melchior, M.Blaser, H.Jaeckel and G.L.Bona; Appl. Phys. Lett. 52(1988) 2130.

12) G.Livescu, A.M.Fox, D.A.B.Miller, T.Sizer, W.H.Knox, A.C.Gossard and J.H.English; Phys. Rev. Lett. 63(1989) 438.

13) W.H.Knox, D.S.Chemla, D.A.B.Miller, J.B.Stark and S.Schmit-Rink; Phys. Rev. Lett. 62(1989) 1189.

14) A.Shimizu and M.Yamanishi, unpublished.

15) M.Yamanishi, Y.Osaka and S.Ago; presented at CLEO/IQEC '90, Anaheim, May 21-25, 1990, Paper No. JTuC3.

16) A.Shimizu and K.Fujii; presented at the annual meeting of Japan Soc. Appl. Phys., Asaka, March 28-31, 1990, Paper No. 30p-PC-23.

17) A.Shimizu, K.Fujii and M.Yamanishi; presented at the annual meeting of Japan Soc. Appl. Phys., Asaka, March 28-31, 1990, Paper No. 30p-PC-24.

18) A.Shimizu, presented at CLEO/IQEC '90, Anaheim, May 21-25, 1990, Paper No. JTuC4.