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Absorption-free modulation of electron-interference currents by optical fields using intersubband virtual transitions

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We propose to modulate quantum interference currents in a semiconductor electron interferometer by optical fields using intersubband virtual transitions, in which the optical fields are subject to no absorptions despite a high modulation efficiency. The electron-light interaction is more direct and efficient than those of previous proposals, and moreover, extra transitions, which could cause absorptions and/or destroy the electron coherence, are almost perfectly suppressed.

It has recently become possible to observe quantum interference currents in small-size ("mesoscopic") metal or semiconductor structures.[1] Most previous work treated modulation of the interference currents either by *static* magnetic or by *static* electric fields (or potentials).[1] A possibility of modulation of the interference currents by *time-dependent* fields (such as optical fields) was first considered by one of the authors (M.Y.).[2] He proposed to drive an electrostatic Aharonov-Bohm (AB) device by a dc voltage generated by optical "virtual" excitations (i.e., optical rectification). The most remarkable point may be that the interference currents can be modulated *without* light absorption. Although in that scheme electron-light interactions are rather indirect ones (i.e., the light field does not interact directly with electrons in the AB device), he recently proposed another scheme in which electrons interact with photoexcited "virtual" excitons through an exchange interaction.[3]

In general terms, these ideas are summarized as follows. Although it is applicable to any time-dependent field, we call the field "optical field" and call the associated quanta "photons" for convenience. Consider the absorption spectra of an electron system in an "optical field." If the "photon" energy lies within a gap of the absorption spectra, the optical field is subject to no absorptions. However, it does *not* mean absence of effects of the optical field upon the electron system. Electron wave functions are slightly deformed by perturbations of an electron-field interaction. By expanding the deformed wave functions in terms of unperturbed eigenfunctions, we can interpret that electrons are *coherently* excited with small amplitudes to excited states.[4] These coherent excitations are sometimes called "virtual excitations."[4] In contrast, when the photon absorptions occur, parts of electrons are *incoherently* excited to excited states, which are called real excitations. The basic idea is use of the slight deformation of electron wave functions induced by virtual excitations. Although the wave-function deformations are, in general, small (less than a few percent, typically), they can have strong effects on electron-interference currents, because a small wave-number change caused by the small wave-function deformation can lead to a large phase shift as an electron travels a distance long compared to its wavelength. As a result, electron-interference currents can be modulated drastically by optical fields without absorptions. From a view point of applications, the total system works as an "absorption-free detector" of the field intensity, because the magnitude of the electron-interference currents varies as a function of the field intensity. This type of device has wide potential applications.[2,3] In particular, it has been recently pointed out that well-designed absorption-free photodetectors work as quantum nondemolition photodetectors.[5]

At first sight, the absorption-free property may look to be inconsistent with a fundamental requirement of quantum mechanics: any measurement must accompany dissipations. In our case, the dissipations *do* occur in classical systems of external apparatus (including contact regions which work as electron reservoirs) which are used to measure the interference currents. However, the dissipations do *not* cause dissipations *in the optical fields* if the measuring apparatus are decoupled from the optical fields, and if the apparatus are *only* coupled with electrons which have *finished* interactions with the optical fields.[5,6] This last point is of particular importance, although it has not been stressed before. In fact, it can be shown[6] that dissipations (absorptions) of the optical fields would occur when the electrons interacting with the optical fields are *simultaneously* coupled with a classical dissipative system, such as a resistor and a transmission line. That is, "virtual excitations" are *not* necessarily free from dissipations of the optical fields.[6]

In this Rapid Communication, we propose a scheme[7] for the absorption-free optical modulation of electron-interference currents, in which electron-light interactions are more direct and efficient than those[2,3] previously proposed, and, more importantly, extra transitions, which could cause photon absorptions and/or could destroy electron coherence, are almost perfectly suppressed. The basic idea is the use of the optical Stark effects of intersubband virtual transitions.[8] Figure 1 shows schematic absorption spectra of a doped quantum-well (QW) struc-

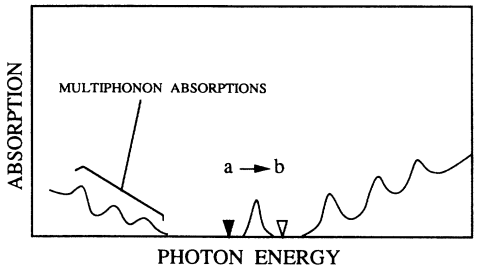

FIG. 1. Schematic absorption spectra of a doped narrow quantum well for the light polarized perpendicularly to the layers. The absorption is negligibly small if the photon energy is just below (as indicated by the solid triangle) or just above (as the open triangle) the absorption peak of the transitions from the first to the second subbands, $a \rightarrow b$. Multiphonon absorptions occur for lower photon energies, while for higher photon energies the absorption spectra approach those of the free-carrier absorptions of a bulk crystal.

ture for the photon energies $\hbar\omega$ in the range of intersubband transition energies.[9] The light is assumed to be polarized perpendicularly to the QW layers. We set the photon energy as

$$\hbar\omega = \varepsilon_b - \varepsilon_a - \Delta , \tag{1}$$

where ε_a and ε_b are the first (a) and second (b) subband energies, and Δ is called the detuning energy. Absorptions and/or scatterings of the light fields are absent if $\hbar\omega \gg$ optical phonon energies and if $|\Delta| > \Gamma$, the width of the $a \rightarrow b$ transitions. Main origins of Γ at low temperatures are QW imperfections and nonparabolicities.[9] Owing to recent rapid progresses in crystal growth techniques, the broadening due to the former has already been greatly suppressed,[10] and is expected to become negligible in the near future.[10] In that case, Γ is almost due to the nonparabolicities which make transition energies different for different values of transverse (parallel to the QW layers) wave numbers. For thin QW's as we will assume below, this Γ may become as large as 10 meV. However, it should be noted that in contrast to other broadening mechanisms this broadening does *not* degrade the device proposed below, because only the states at the Fermi level carry currents and the width of each of the states is much smaller than Γ. Their contributions in the absorption spectra appear at the lower-energy edge of the $a \rightarrow b$ absorption peak. All we have to do is to replace $\varepsilon_b - \varepsilon_a$ in Eq. (1) by this lower energy.

There are many reasons for using intersubband virtual transitions rather than interband ones: (i) Extra transitions, such as interband transitions and free-carrier scatterings, are almost perfectly suppressed. In contrast, if one used interband transitions, the light not only would induce interband virtual transitions but also would interact directly with conduction electrons. This could cause photon absorptions and/or could destroy electron coherence. (ii) The transition dipole moment is very large,[9] which leads to smaller light intensity to modulate currents. (iii) Electron density can be made very high because it is unnecessary to maintain excitons as in Ref. 3. As a result, a large Fermi velocity v_F is obtained, which leads to a high operation speed, a long coherence length ($l_\phi = v_F \tau_\phi$), and a high monochromaticity ($\delta k/k_F \sim k_B T/\varepsilon_F$) of electron waves.[1] (iv) It is possible to make Δ negative as well as positive, as seen from Fig. 1. Consequently, as explained below, the optical fields need not be focused upon a very small spot as in previous work,[2,3] and also the optical Stark shifts of two arms can be utilized constructively [see Eq. (10) below]. (v) The operation wavelength is compatible with ultralow-loss optical communications.[11]

Figure 2 shows the proposed structure. This is based upon the electrostatic AB effect device proposed by Datta *et al.*[12] To modulate interference currents, they utilized a change in electrostatic potential, whereas we utilize the optical Stark shifts of subband levels induced by optical fields,[8] as explained below. Two quantum-well wires (QWW's) *of different well widths,* the narrow (N) and the wide (W) ones, constitute an AB geometry. The ring should be made within the coherence length l_ϕ of electrons, which is of the order of 10 μm at 1 K.[1] For simplicity we further assume that the electrons move ballistically,[1] although the interference may also occur in the diffusive case.[1] We also assume that the confining potential in the y direction is common for the two QWW's, so that they have the same eigenfunction $\phi_y(y)$ and eigenenergy ε_y. For the z direction, we denote the lowest-subband energy and wave function in N or W by $\varepsilon_a^{N,W}$ and $\phi_a^{N,W}(z)$, respectively, and the second-subband energy by $\varepsilon_b^{N,W}$. By appropriately designing the widths and alloy compositions of the wells, we can easily make the subband energies to satisfy the relations

$$\varepsilon_a^N = \varepsilon_a^W \equiv \varepsilon_a , \tag{2}$$

$$\varepsilon_b^W - \varepsilon_a^W < \hbar\omega < \varepsilon_b^N - \varepsilon_a^N . \tag{3}$$

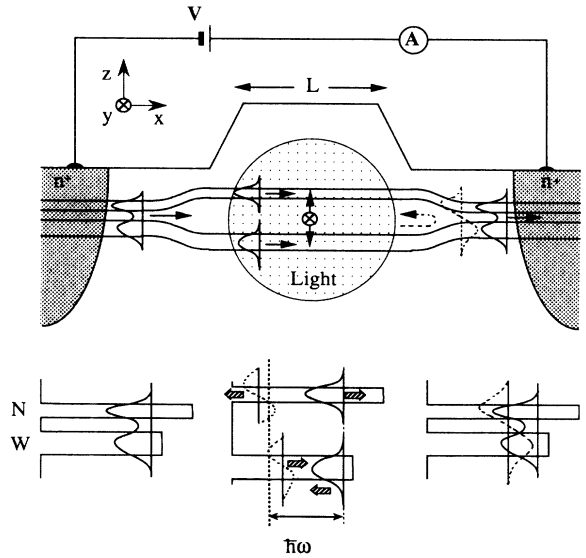

FIG. 2. Schematic diagram of the proposed structure. The large circle represents the cross section of the light beam. The electrons at the Fermi level flow from left to right. The band diagrams and eigenfunctions in the left, middle, and right regions are shown in the lower side. In the middle band diagram, the arrows indicate the directions of the optical Stark shifts of the subband energies.

In the coupling regions lying between the ring and the contact regions, the lowest subband state is given by

$$\phi_S = (\phi_a^N + \phi_a^W)/\sqrt{2} . \quad (4)$$

At temperatures lower than the energy separation between this state and the second-subband state, an electron which is injected from the left-contact region into the left-coupling region is in this ϕ_S state.[12] Despite the difference in the well widths of N and W, the weights of ϕ_a^N and ϕ_a^W are equal in ϕ_S, as in Eq. (4), owing to the relation (2). Hence, as an electron proceeds to the ring region, its wave function will just be halved into two parts: $e^{ikx}\phi_y(y)\phi_a^N(z)/\sqrt{2}$ and $e^{ikx}\phi_y(y)\phi_a^W(z)/\sqrt{2}$, where k is the wave number of the motion in the x direction and is related with the Fermi energy ε_F by

$$\varepsilon_F = \hbar^2 k^2/2m^* + \varepsilon_y + \varepsilon_a , \quad (5)$$

with m^* being the effective mass. In the center region (we call it the interaction region) of the ring region, a z-polarized optical beam propagating in the y direction is shown. In this interaction region, $\varepsilon_a^{N,W}$ is slightly changed due to the optical Stark effect by[8]

$$\Delta\varepsilon_a^{N,W} = -|\mu_{N,W}\mathcal{E}|^2/\Delta_{N,W} , \quad (6)$$

where $\mu_{N,W}$ is the $\phi_a^{N,W} \rightarrow \phi_b^{N,W}$ transition dipole moment,[8,9] $\mathcal{E}$ is the electric-field amplitude of the optical field, and $\Delta_{N,W}$ is the detuning energy. As a result of the above optical Stark shift of $\varepsilon_a^{N,W}$, the wave number k is also changed in the interaction region according to Eq. (5) by

$$\Delta k_{N,W} = (k + 2m^*\Delta\varepsilon_a^{N,W}/\hbar^2)^{1/2} - k . \quad (7)$$

After the electron passes through the interaction region, the two parts of its wave function in the two QWW's acquire the relative phase difference given by

$$\Delta\theta \simeq (\Delta k_N - \Delta k_W)L + \Delta\theta_0 , \quad (8)$$

where L is the length of the interaction region (i.e., the width of the optical beam) and $\Delta\theta_0$ is an offset phase difference caused by possible difference in the path lengths along the two QWW's. While entering the right-coupling region, only the in-phase part of the wave function can go into the coupling region, [12] Hence, if we neglect multiple reflections for simplicity, the conductance G between the two contact regions varies as[12]

$$G \propto \cos^2(\Delta\theta/2) . \quad (9)$$

Since $\Delta\theta$ is a function of the light intensity I ($\propto |\mathcal{E}|^2$) as seen from Eqs. (6)–(8), G varies with I. To get larger $\Delta\theta$ for a given value of I, it is particularly effective to make Δ_N and Δ_W different in signs; $\Delta_N > 0$ and $\Delta_W < 0$. (This is possible for intersubband virtual transitions.) In that case, the directions of the optical Stark shifts in the two QWW's become opposite, as indicated by the arrows in Fig. 2, and consequently the two QWW's contribute *constructively* to $\Delta\theta$ in Eq. (8):

$$\Delta k_N - \Delta k_W = |\Delta k_N| + |\Delta k_W| . \quad (10)$$

If we assume GaAs/AlAs QWW's of about 40-Å well thickness, the photon wavelength λ becomes about 2.8 μm, which is compatible with ultralow-loss optical communications.[11] We also assume the beam width $L \sim \lambda/$(refractive index) $\sim 1\ \mu$m, the detuning energies $\Delta_N \approx -\Delta_W = 10$ meV, and the electron density $\sim 10^6\ \text{cm}^{-1}$. Then, G is modulated over 50% at the light intensity of $I \simeq 2\ \text{MW/cm}^2$, which intensity is an order of magnitude smaller than those of previously proposed structures.[2,3] Since the beam area is 1 μm^2, the light power is only 20 mW, and its fraction hitting upon the QWW's is as small as about 0.2 mW.

In the above discussions, we have assumed that the light-induced level shifts are due to the *pure* optical Stark shifts as observed in simple atomic systems. In other words, many-body effects, which were important in the case of Ref. 3, have been assumed to be unimportant in our case of intersubband virtual transitions. Although this was experimentally confirmed in an *undoped* QW,[8] no experiments have been performed for *doped* QW's or QWW's. We evaluated many-body corrections using a simple theory and found that they are indeed very small for intersubband *virtual* excitations in *thin* QW's or QWW's.[13] This conclusion should be contrasted with the case of intersubband *real* excitations where many-body corrections to the subband energies are important.[9,13] Although the theoretical result[13] may need an experimental test, we note that Eqs. (7)–(9) are valid irrespective of origins of the level shifts. Hence, the currents can be modulated even if the many-body effects played a role.

We finally consider the feasibility of observing the proposed effect. The structure of Fig. 2 or of Ref. 12 has not been fabricated so far. However, we note that our proposed effect does not depend on the specific structure of the electron interferometer. That is, the absorption-free optical modulation of electron-interference current should be observable in any electron interferometers whose interference patterns are altered by intersubband virtual transitions. For example, the effect should also be observable in the resonant tunneling diode of Fig. 3 of Ref. 5, or in the electron interferometer of Ref. 14, in which the exact 1:1 branching ratio as well as the single mode transmission in an AB ring can be achieved by forming a ring-shaped electron path in a *straight* double-quantum-wire structure by control of wave functions by gate voltages.[14] Another possibility of observing the effect is to observe changes in magnetoresistance[15] in an AB ring structure caused by intersubband virtual transitions. Experiment on these possibilities is in progress.

In summary, we have proposed a scheme for an absorption-free optical modulation of electron-interference currents. The electron-light interaction is more direct and efficient than those previously proposed, and, more importantly, extra transitions, which could cause photon absorptions and/or could destroy electron coherence, are almost perfectly suppressed. Among structures ever proposed, the most efficient current modulation has been achieved.

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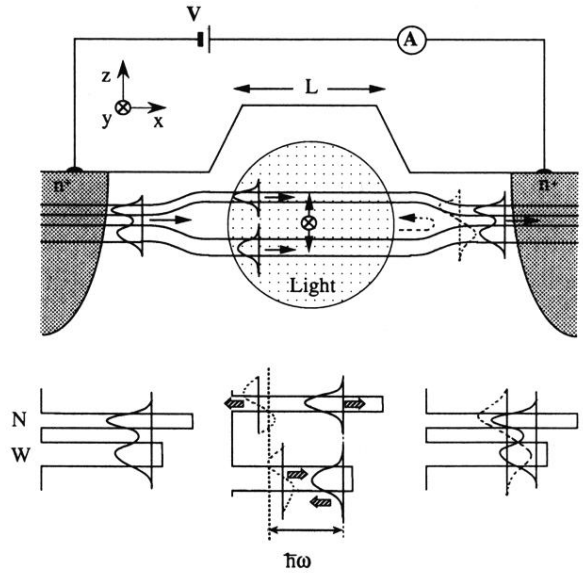

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