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# Novel electro-optical phase modulator based on GaInAs/InP modulation-doped quantum-well structures

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A novel electro-optical phase modulator working at 1.55 $\mu$m is analyzed and proposed. It is shown by a numerical model that in a GaInAs/InP *pn-nin-pn* multiple-quantum-well waveguide structure, large optical phase modulation can be obtained at small intensity modulation and with improved performance compared to what is achieved in quantum confined Stark effect modulators of the same material system. The device proposed is based on a modulation of the quasi-Fermi energies of the electrons in the GaInAs quantum wells. This operational principle allows GHz modulation frequencies.

There is currently much interest in optoelectronic devices based on carrier-induced modulation of the absorption and the refractive index.[1-4] Carrier-induced modulation can appropriately be described as a change in the position of the quasi-Fermi energies of the electrons and the holes. In this letter, a numerical model is presented which calculates electrical-controlled modulation of the quasi-Fermi energies in modulation-doped quantum-well structures. Based on the results of the modeling, a novel device for optical phase modulation at 1.55 $\mu$m is proposed: a GaInAs/InP *pn-nin-pn* multiple-quantum-well (MQW) waveguide structure. It is shown that in this structure a large improvement in the ratio between the change in the refractive index and the change in the extinction coefficient is obtained when compared to what is achieved in quantum confined Stark effect (QCSE) modulators of the same material system. A high value of this ratio is desirable for devices which require pure optical phase modulation without intensity modulation.

In order to determine the quasi-Fermi energies in the quantum wells (QWs), the following equations have been solved: the Poisson's equation (1), the transport equations for the electrons (2), and for the holes (3), the continuity equations for the electrons (4), and for the holes (5), and the Schrödinger's equations in the effective mass approximation for the electrons (6), and for the holes (7) in the QWs. For the transport equations, diffusion and drift have been assumed in the InP bulk material. In the QWs, a purely two-dimensional (2D) density of states was used with thermionic emission and capturing from the wells.[5] The generation/recombination term in the continuity equations includes Shockley–Read–Hall recombination $\tau_{SRH}$, spontaneous emission recombination $B_{sp}$, and Auger recombination $C_{Auger}$. The potential energy in the Schrödinger's equations for the electrons and the holes contains the band offset, the electric field, and a parameterized form of the local exchange correlation energy[6] responsible for the band-gap shrinkage effect. A finite difference method was used to solve the Poisson's equation, and the transport equations and the continuous equations were solved using a Scharfetter–Gummel scheme.[7] The electron and the hole states in the QWs were determined using a tunnel resonance method.[8] All seven equations were solved self-consistently with the usual boundary conditions for the contacts.[7] The material parameters used were taken from the literature,[9-12] where the following figures reported in Ref. 12 were employed for the recombination in the GaInAs/InP MQW region: $\tau_{SRH}=10^{-6}$ s; $B_{sp}=1.2\times10^{-10}$ cm$^3$/s; and $C_{Auger}=9\times10^{-29}$ cm$^6$/s.

Figure 1 shows the results of modeling the position dependence of the energy bands of a GaInAs/InP MQW *pn-nin-pn* structure. The voltage applied is set equal to (a) $-2$, (b) 0, and (c) $+1$ V. In the structure, the intrinsic ($i$) region contains 10 periods of 40 Å GaInAs QWs and 80 Å InP barriers surrounded by 500 Å InP cladding layers. A calculation of the power filling factor for the QWs yields, $\Gamma_{QWs}=0.05$. The doping densities are assumed to be $2\times10^{18}$ cm$^{-3}$ for the two $p$ regions and the back $n$ region, and $5\times10^{16}$ cm$^{-3}$ for the 0.2-$\mu$m-wide $n$ regions surrounding the intrinsic MQW region. This configuration provides a symmetric injection of carriers into the MQWs at forward bias.

At a voltage of $-2$ V, the QWs are depleted of carriers [see Fig. 1(a)]. The electric field across the MQW region is less than 20 kV/cm and the QCSE is negligible. At zero voltage [see Fig. 1(b)], electrons are introduced into the QWs and the Fermi level lies close to the subband of the electrons (there is one electron subband and five hole subbands in the QWs). At a voltage of $+1$ V [see Fig. 1(c)], both electrons and holes are injected into the MQW region. A large number of states of the single electron subband are now occupied, but only a small fraction of the hole subbands are occupied, since the hole density of states is more than one order of magnitude larger than the electron density of states. This means that the electrons are mainly responsible for the band-filling effect.

A simple model can be used to estimate the effect of carrier injection on the absorption. Figure 2 shows a calculation of the absorption coefficient for the 40 Å GaInAs MQW structure at different voltages as indicated. The absorption coefficient in absence of carriers was determined by calculating the heavy hole and the light hole exciton oscillator strengths for the GaInAs QWs using a variational approach with a 2D trial exciton envelope function[8]

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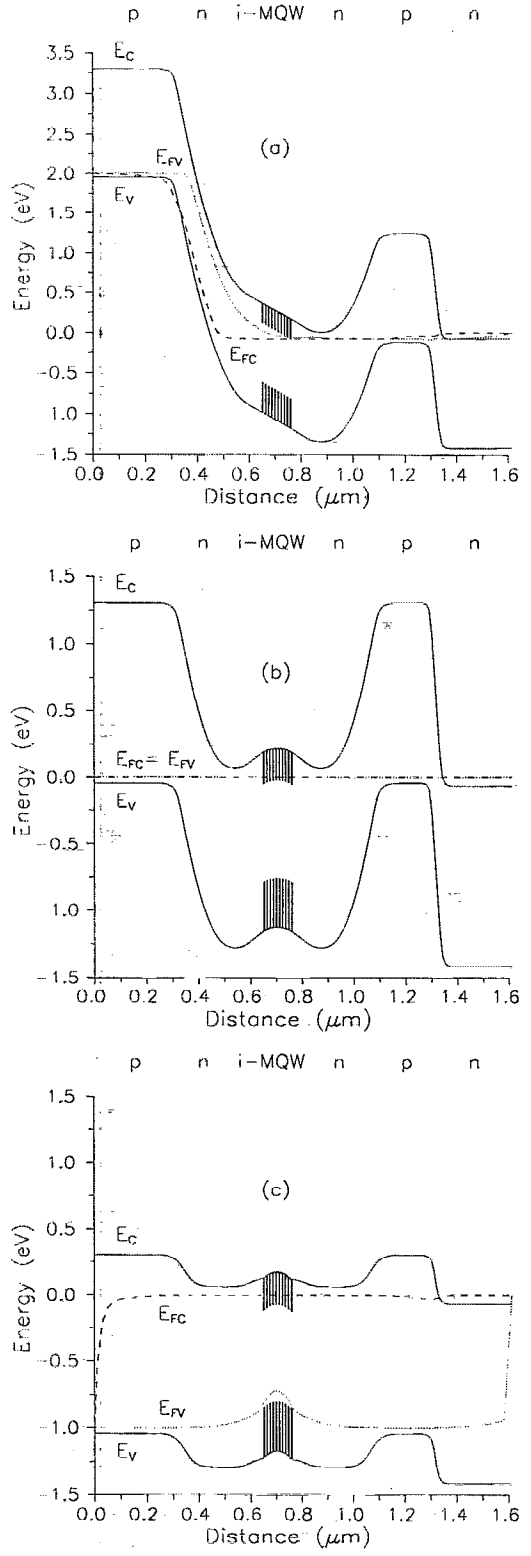


FIG. 1. Calculated conduction band $E_c$ and valence band $E_v$ (solid lines), quasi-Fermi energy for the electrons $E_{FC}$ (dashed lines), and quasi-Fermi energy for the holes $E_{FV}$ (dotted lines) for the GaInAs/InP *pn-nin-pn* MQW structure; (a) $V=-2$ V, (b) $V=0$, and (c) $V=+1$ V.

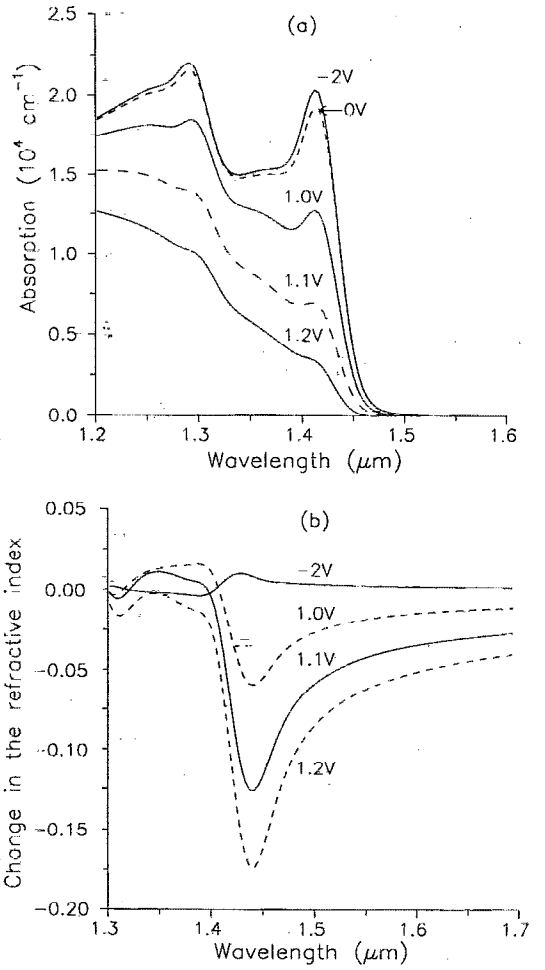


FIG. 2. Calculated absorption coefficient (a) and change in the refractive index (b) for the GaInAs/InP *pn-nin-pn* MQW structure at different applied voltages as indicated.

and assuming a pure 2D exciton continuum. This procedure has shown to give good agreement to experimental data.[13] The absorption coefficient in presence of carriers was determined by including the exchange correlation effect in the calculation of the excitonic absorption and taking account of the band-filling effect by multiplying the contribution from each exciton by the difference between the Fermi function for the hole and the Fermi function for the electron belonging to the exciton. These two carrier effects have shown to be dominant in quantum wells.[14]

The corresponding change in the refractive index is shown in Fig. 2(b) and it was obtained by performing the Kramers–Kronig transform on the absorption changes $\Delta\alpha(\lambda)$ from Fig. 2(a);

$$\Delta n(\lambda)=\frac{\lambda^2}{2\pi^2}P\int\frac{\Delta\alpha(\lambda')}{\lambda^2-\lambda'^2}d\lambda', \tag{1}$$

where $\lambda$ is the wavelength of light and $P$ denotes the principle value of the integral.

By working at a wavelength of 1.55 $\mu$m, it is possible to get large refractive index changes and small absorption changes at the same time (see Fig. 2). For example, when the voltage is modulated from $-2$ to $+1$ V, a $\Delta n=0.021$ is obtained. The corresponding change in the carrier density in the MQW region is $\cong 3\times 10^{17}$ cm$^{-3}$, and using reported values for bulk GaInAsP[15] this gives a free-carrier absorption coefficient of approximately 10 cm$^{-1}$. In this

case, the ratio between the change in the refractive index $\Delta n$ and the change in the extinction coefficient $\Delta k = \lambda \Delta \alpha / 4\pi$ is, $\Delta n / \Delta k = 170$.

In order to obtain a similar change in the refractive index from the QCSE, it is necessary to operate closer to the absorption edge. The numerical model predicts that for the present QW structure and an electrical field of 100 kV/cm, the QCSE yields $\Delta n / \Delta k = 6.5$ with $\Delta n = 0.01$. This is comparable to what has been achieved in optical phase modulators working at $\sim 1.55$ $\mu$m and based on the QCSE in GaInAsP quantum wells. [16] The structure proposed here therefore provides a large improvement in the ratio $\Delta n / \Delta k$.

The reason for this can be explained from the Kramers–Kronig relation [see Eq. (1)]. The QCSE is based on an electric-field-induced displacement of the exciton peaks combined with a reduction in the oscillator strengths of the peaks.[8] At long wavelengths $\lambda$ where the absorption coefficient is low, $\lambda^2 - \lambda'^2$ in Eq. (1) has the same sign throughout the region with a large absorption change $\Delta \alpha$, and the QCSE produces a negative $\Delta \alpha$ above the heavy hole exciton peak and a positive $\Delta \alpha$ below this peak. The two contributions therefore tend to cancel each other in Eq. (1). On the contrary, the band-filling effect solely produces a negative $\Delta \alpha$, and as depicted in Fig. 2 large refractive index modulation can be achieved in the region with low absorption.

For a voltage change from $-2$ to $+1$ V, the calculation of the carrier effect shows that the electrons are responsible for 91% of the change in the refractive index. This is an advantage in terms of speed: an estimation of the thermionic emission time[5] from the QWs yields 8 ps for the electrons, but 160 ns and 50 ns for the heavy hole and the light hole, respectively. The recombination time of the carriers in the QWs is of the order of 20 ns. At high modulation frequencies, the holes therefore accumulate in the QWs where they tend to screen the electric field across the MQW region, and complicates sweeping out the electrons from the QWs. However, by assuming that the holes are accumulated at a density corresponding to an applied voltage of $+1$ V, the numerical model shows that a negative voltage of $-8$ V is able to deplete the MQW region of electrons. The estimated thermionic emission time combined with drift and diffusion to the $n$ contact gives a total electron lifetime of 48 ps, which sets the speed limit for the present device configuration.

In an actual waveguide modulator, the speed may be limited by the RC constant. For a $\pi$ phase shift of the light, the required length of the waveguide is, $L \cong \lambda / 2 \Delta n \Gamma_{QWs} = 800$ $\mu$m, where $\Delta n \cong 91\% \times 0.021$. Assuming a 2-$\mu$m-wide waveguide and a 50 $\Omega$ drive, the theory of forward-voltage capacitance[17] yields an RC constant of $\cong 100$ ps and modulation frequencies in the GHz regime.

In conclusion, a model has been presented which determines the electrical-controlled modulation of the quasi-Fermi energies in modulation-doped QW structures. The model predicts that large optical phase modulation with small intensity modulation can be achieved in a GaInAs/InP *pn-nin-pn* MQW waveguide structure. In the device proposed, GHz modulation frequencies are theoretically possible with a largely improved $\Delta n / \Delta k$ ratio compared to what is achieved in QCSE modulators of the same material system.


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