Optimization of InGaAsP-based BRAQWET heterostructures

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Abstract

A new class of optical switching structures has been recently proposed, the barrier resevoir and quantum well electron transfer structures (BRAQWETS), which are based on the voltage-control transfer of electrons in multiple-quantum wells. This type of modulators provides stronger electro-absorption and refraction than structures based on the quantum confined Stark effect, although the optical confinement is smaller due to the necessarily limited number of quantum wells. The purpose of this presentation is to investigate the fabrication and the basic physics of InP-based BRAQWET structures toward optimization of device performances.

Introduction

The availability of highly performant semiconductor-based electro-optical modulators is crucial for the development of optical fiber telecommunication systems. The optical properties of semiconductors can be modified by varying the concentration of free carriers inside the material. This occurrence is particularly apparent in quantum well (QW) structures due to the presence at room temperature of excitons, *i.e.* bound electron-hole states, which are especially unstable with respect to the interaction with the thermalized plasma of carriers [1, 2]. As the existence of excitons is connected with spectral structures showing rather sharp peaks, their instability can be exploited to induce significant changes in the spectral response and, consequently, in the electromagnetic propagation conditions of optical waveguides including multiple QW structure [3]. Free carriers can be introduced in QW structures in various ways: one of the most immediate is the transfer of electrons across a heterojunction, as it is the case of BRAQWET (Barrier Reservoir and Quantum Well Electron Transfer) devices. BRAQWET structures have been shown to be very promising for electrically-controlled light modulation, the modulation being based on the quenching of the absorption coefficient in the QW upon phase-space filling effects [1].

The operation of BRAQWET devices involves the transfer of electrons over nanometer-scale distances, from a n-type reservoir to a closely-spaced QW; thus, the relevant transit time is small and fast operation can be achieved [4]. The refractive index variation, and the related phase modulation that can be reached in a BRAQWET device, are generally larger than those obtained in electrooptical devices that exploit the quantum-confined Stark effect [5]. When integrated with light emitting or amplifying devices, BRAQWET structures might prove useful in the fabrication of fast tunable lasers or filters.

Earlier structures had generally been based on the InGaAlAs material system [6], but most of the technological expertise that have been developed within optoelectronics and photonics for telecommunications is based on InGaAsP and related materials. In this respect, BRAQWET structures based on this latter material class posses a stronger technological potential [7, 8, 9, 10]. However, some limitations, due either to strong leakage current or to insufficient charge transfer to the QW occur, which are peculiar to the InGaAsP material system [7, 8].

In this paper a model to study a type of BRAQWET structures and to evaluate its performances is presented, and it is applied to the optimization of the device; moreover the speed limitation due to tunneling phenomena is discussed.

Device model

The purpose of this paper is to study the performance of InGaAsP- based BRAQWET devices aimed at obtaining sizeable refractive index modulation at photon energy corresponding to the wavelength of 1.55 μm. To this end, we start with one particular structure, which we regard as a reference device, and then we vary some of the structural parameter values in order to explore the effects on the charge build-up inside the QW. The layer sequence in the reference structure is depicted in Table 1, where the quaternary layers in the structure correspond to an energy gap of 0.955 eV. The n-layer is Si-doped, while in the p-region a Be-doping is used.

To properly model a BRAQWET device, the common hypothesis of negligible current flow is assumed, which is a good approximation up to a certain polarization due to the peculiar conduction band energy profile. Moreover only electrons are supposed to contribute to the carrier density. The spatial behavior of the conduction band structure (and the consequent valence band) has been computed by solving the Poisson equation coupled with the Schrödinger equation. In fact the electric field inside

Layer	Material	Width	Doping
Reservoir	InGaAsP	500 Å	n = 10^{18}cm^{-3}
Spacer 1	InGaAsP	250 Å	intrinsic
QW	InGaAs	90 Å	intrinsic
Barrier	InP	250 Å	intrinsic
Barrier	InP	150 Å	p = 10^{18}cm^{-3}
Barrier	InP	150 Å	intrinsic
Spacer 2	InGaAsP	120 Å	intrinsic

Table 1: Definition of the reference structure

the structure is determined by the carrier distribution through the Poisson equation. Hence the self-consistent solution of the following system is required:

$$\frac{d^2V}{dz^2} = \frac{q}{\varepsilon}(N - N_d) \quad (1)$$

$$-\frac{\hbar^2}{2m}\frac{d^2\Psi_i}{dz^2} + V(z)\,\Psi_i = E_i\,\Psi_i \quad (2)$$

where the z axis is oriented along the grouth direction, Ψ_i is the wavefunction of the electron in the potential field V and E_i are the corresponding energy levels. In all the structure, excluding the QW, the contribution to the carrier density N due to the continuum spectrum of energy levels is considered, according to the Fermi-Dirac statistics; in the regions interested the quantized carrier density contribution is added by summing up the weighted contributions of all the bidimensional sub-bands:

$$N = \sum_i |\Psi_i|^2 N_i \quad (3)$$

being N_i given by:

$$N_i = \frac{mk_BT}{\pi\hbar^2}\ln\left[1 + \exp\left(\frac{E_f - E_i}{k_BT}\right)\right] \quad (4)$$

where E_f is the quasi-Fermi level.

In (1) N_d is the ionized dopant density which is related to the dopant concentration N_0 by the following relation [11]:

$$N_d = \frac{N_0}{1 + 2e^{(E_f - E_a)/k_BT}} \quad (5)$$

being E_a the dopant activation energy.

The effect of non-completely-ionized dopants is very important, particularly with the high doping concentrations considered, where, from (5), N_d/N_0 approaches 1/3. In fact (5) has been used only for the n-doped layer, while the the p-region can be considered completely ionized in usual conditions.

Also the bandgap renormalization due to carriers has been included in the model [1], which in (1) to (4) influences the dependence of N on the quasi-Fermi level.

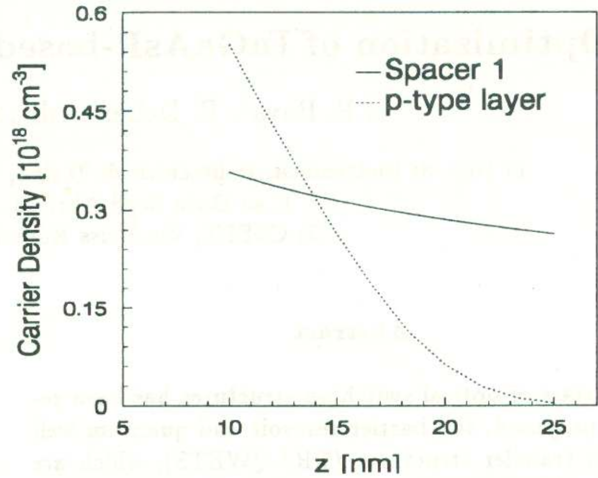

Figure 1: Carrier density that is predicted to be moved to the QW as a function of the thickness of the spacer 1 (solid line). The dotted line represents the corresponding behavior when the thickness of the p-type layer is varied.

E_f is evaluated in the reservoir region including the effects of the dopant ionization and band-gap renormalization, and then it is kept constant through the BRA-QWET up to the QW, since the current flow is assumed negligeable.

The self consistent solution of (1) and (2) is obtained iterativelly as follows:

- analytical evaluation of $V(z)$ by the solution of (1) starting from the distributions of N and N_d corresponding to a fully depleted model,
- numerical solution of the Schrödinger equation (2) using for the potential profile the result of the preceding step,
- numerical solution of the Poisson equation taking into account the charge distribution in the well obtained in the previous step,
- the last two steps are iterated till convergence, which is estimated through the variation of the first energy level in the QW.

For the Poisson equation a finite difference technique has been used in which the discretization step can be chosen different in each layer.
The Schrödinger equation is solved analytically in each uniform region defined by the adopted discretization; the complete solution is obtained by imposing the boundary conditions at all the discretization layer interfaces. For simplicity the Schrödinger equation was considered only in the first four layers of the described structure, since the wavefunctions of interest are essentially localized in that region.

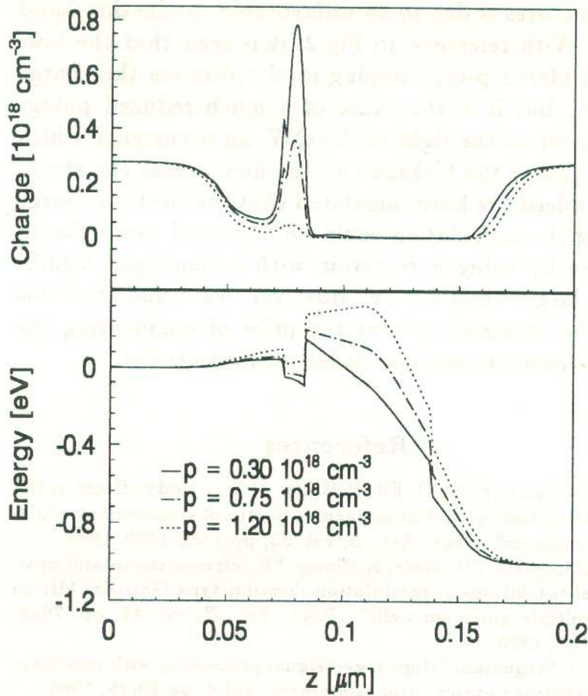

Figure 2: Carrier density and conduction band profiles under 1 V applied bias. The curves represent the behavior at varying doping level in the p-type region, when three different dopant concentrations are considered. In the calculation, the Schrödinger and Poissons equations are iterated to mutual consistency, in the presence of a renormalized bandgap.

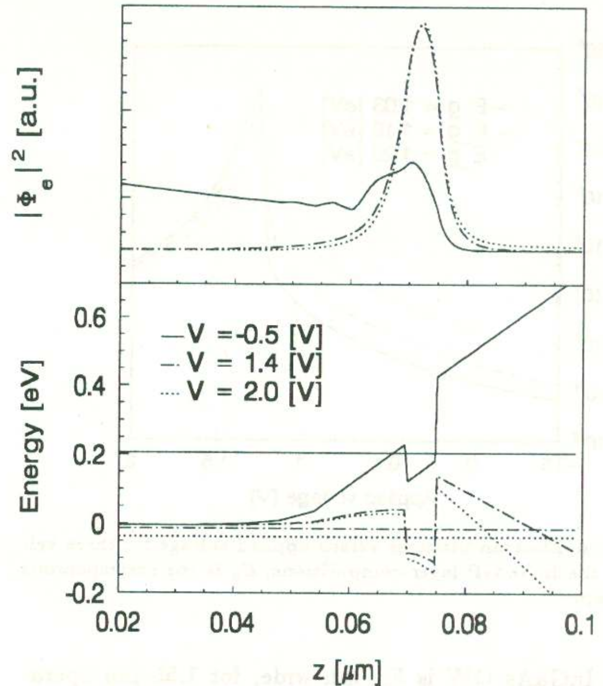

Figure 3: Conduction band profiles and corresponding electron wavefunctions in the optimized BRAQWET structure for three values of applied voltages.The horizontal lines represent the values of the corresponding energy levels. Only a limited portion of the structure is shown, where the wavefunction is considered.

Generally the energy eigenvalues are complex since the electron wavefunctions are not strictly localized; the imaginary part is related to the particle lifetime τ by means of the following relation:

$$\tau_i = \frac{\hbar}{\mathrm{Im}(E_i)} \qquad (6)$$

which is of interest in the evaluation of the device speed limitation due to tunneling.

Device optimization

The model described in the preceding section has been exploited to optimize the BRAQWET electrooptic response and then to provide useful information for an optimized structure.

The optically-active part of the structures investigated here is based on the sequence InGaAsP / InGaAs / InP, forming a QW with asymmetrical barriers, where the energy gap of the quaternary layer is about 1.0 eV. The rightmost barrier should be as high as possible, being designed to prevent undesired current flows taking place in the conduction band across the structure under high direct polarization. In this respect the InGaAlAs material system should be preferable, since InAlAs would provide a much higher potential barrier than InP.

In the evaluation of the BRAQWET performances both the geometrical parameters of the various layers and the doping levels in the n and p regions have been varied, with the purpose of maximizing the amount of charge that it is possible to displace to the QW. In particular, the spacer 1 and p-type layer thicknesses have been varied within the range 10-25 nm. The results are represented in Fig.1, where the carrier density build-up N_i/d (where d is the well thickness) in the QW, under a 1V direct bias is shown. It can be observed that steep variations are expected by modifying the thickness of the p-type layer. Another factor which critically affects the charge transfer is the doping level in the p-type region. The reason for such a behavior is that the total amount of charge in the p-type layer is responsible of the band banding in the structure, in particular near the QW, and so strongly influences the charge transfer from the reservoir.

The band profiles corresponding to three different p-doping levels are depicted in Fig.2, which shows the conduction band diagram under a 1 V direct bias and the corresponding carrier density profiles.

On the basis of the previous results the optimized structure differs from the reference one as follows:
– a 60 nm reservoir (n=2x10^{18} cm^{-3}) with composition corresponding to E_g= 1.03 eV is followed by a 10 nm, InGaAsP intrinsic spacer,

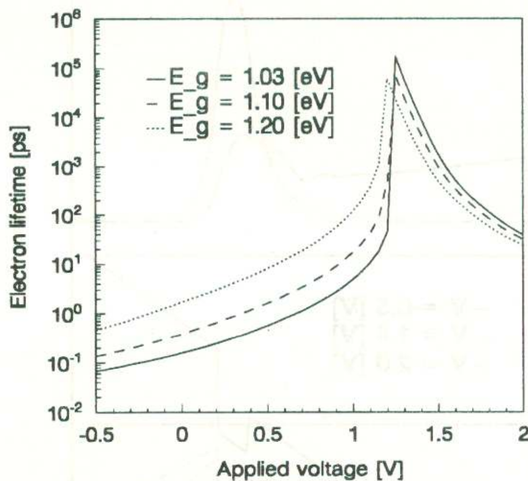

Figure 4: Electron lifetimes versus applied voltage for three values of the InGaAsP layer compositions; E_g is the corresponding bandgap.

- the InGaAs QW is 5.0 nm wide, for 1.55 μm operation,
- the doping concentration in the corresponding InP layer was reduced to 0.75x10^{18} cm^{-3},
- the last layer thickness was changed to 16 nm.

For this optimized device, the computed band structure and the corresponding wavefunctions for three values of applied voltage are reported in Fig. 3; in this case only one discrete energy level exists.

The electron lifetime, computed from (6) is shown in Fig. 4 as a function of the applied voltage, for three different compositions of all the InGaAsP layers (the continuous line refers to the optimized structure considered in Fig. 3).

By comparing Fig. 3 and 4, one can observe that up to a certain voltage the wavefunction is not well confined on the reservoir side; this corresponds to a very small particle lifetime due to tunneling. When the direct applied voltage is too large (dotted line in Fig. 3), the wavefunction spreads out towards the p-doped region; this effect gives rise also to an undesired increase of leakage current. It follows that there is an optimum voltage range in order to limit the leakage. Fast device operation, if limited by theelectron tunneling from the quantum well to the reservoir, can be achieved, being the electron lifetime of the order of 1 ps near 0 applied voltage.

Conclusions

Besides some technological merits, InGaAsP BRAQWET structures have, in general, exhibited a few but serious limitations, that need appropriate solution in order to fully exploit their potential in waveguiding applications. The most challenging problem peculiar to InGaAsP-based structures is due to an unfavorable conduction-band offset. With reference to Fig.2, it is seen that the lowest considered p-type doping level optimizes the charge transfer, but it is the cause of a much reduced potential barrier on the right of the QW, an occurrence which would favour the leakage current flow across the structure. Indeed, we have calculated that the electron charge causing the modulation could be increased over a factor of three by using a reservoir with a band gap significantly larger than 1.0 eV. However, we found that this could be obtained only at the price of augmenting the leakage current over two orders of magnitudes.

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