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THEORETICAL AND EXPERIMENTAL STUDY OF COUPLED ASYMMETRIC QUANTUM WELL OPTICAL SWITCHES

Andrea Reale*, Aldo Di Carlo , and Paolo Lugli
INFM and Dipartimento di Ingegneria Elettronica
Università di Roma "Tor Vergata", I-00133 Roma, Italy

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ABSTRACT

We present a joined theoretical and experimental study of an optical switch based on an asymmetric double quantum well structure. The energy band profile for the device in the presence of the optical field has been calculated using a coupled 1-D Schrödinger-Poisson solver. The absorption spectra are then calculated and compared to the experimental ones, indicating the importance of non-linear effects such as band-gap renormalization.
The dynamical response of the device to a train of periodic pulses has been investigated by mean of a proper set of rate equations drawn by a quite general model including all important transport phenomena.

I. INTRODUCTION

The possibility of developing all-optical communication networks relies greatly on the understanding of optical non linearities, the basic mechanisms for many different optoelectronic devices requiring logical functions in optical nodes. Optical manipulation of information is one of the most exciting trend in optoelectronic technology, necessary to overcome the bottleneck of electro-optical signal conversion and to bring a full use of optical fiber pass-band.

Optical switching [1]- [3] is one of the main problems of routing that photonics is going to face, because it does not simply require to move Gbit/s multiplexed channels as a whole, but it implies instead breaking the high data rate channel down to its constituent parts, reassembling them in a different order, and redirecting them to different channels for transmission to a variety of destinations. In this work we present the modeling of an Asymmetric Coupled Multiple Quantum Well (ACMQW) structure in steady-state and dynamical conditions. ACMQW structures has been considered from many authors [4] as possible candidates for very fast optical switches.

The switching device we studied consists of 30 periodic cells, each one with the structure shown in Fig.1. Barriers between cells (110 $\AA$) and between wells (80 $\AA$) are made of InP, the thin wells (47 $\AA$) are of $In_{0.47}Ga_{53}As$, the large well (500 $\AA$) is $In_{0.47}Ga_{53}As_{0.8}P_{0.2}$.

In this work, we have investigated the possibility that a charge dipole forms, due to separation of carriers between large and thin well, under strong optical pumping. In fact, if electrons would accumulate in the larger well, acting as a semiclassical reservoir (R), and holes in the thin well (W), the resulting dipole field could trigger a non linear response of the structure.

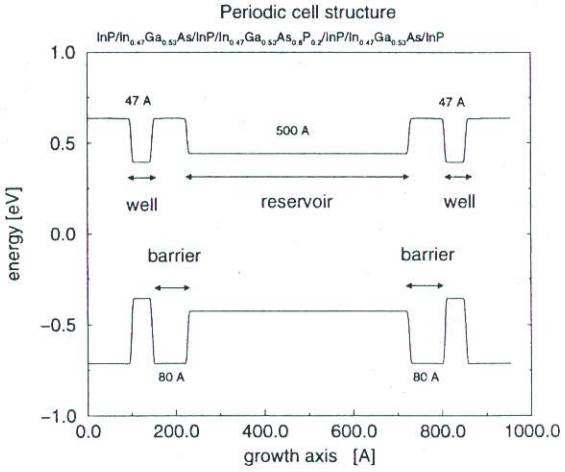

FIG. 1. Periodic cell structure of the ACMQW device

This paper is organized as follows: we first present the analysis of the response of the ACMQW device under stationary excitation, while in the second part we defined a model for the dynamical behaviour of carriers.

In all the models developed we considered only free carrier contribution, neglecting completely excitonic effects. Such approach should be justified by the different time scale of the various processes inside the semiconductor, very fast (in the femtosecond range) for creation/deexcitation of excitons, and much slower (picoseconds) for free carriers.

II. CW EXCITATION AND NON-LINEAR EFFECTS IN ACMQW

Quantum confined structures can show optical non linearities for many different reasons. One of the more interesting process bringing non linear behaviour is the quantum Stark effect, i.e. rearrangement of energy levels inside a quantum well under the effect of an external electric field applied to the structure. Optical non lin-

earities arises from modifications of the optical matrix element. Other mechanisms, such as energy renormalizations, can also originate non-linear behaviours and, generally speaking, all these effects should be considered in order to investigate the optical response of a semiconductor nanostructure.

In Fig.2, we show the CW transmittance measurement [5], at different optical field intensity, for the structure depicted in Fig.1. It's clear from the figure that there is a strong red shift of transmittance spectrum as intensity increases.

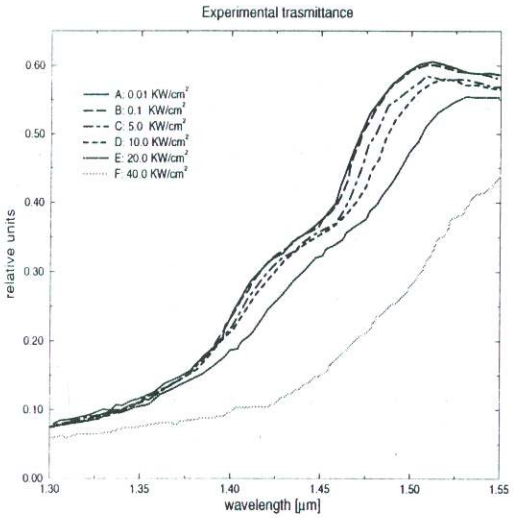

FIG. 2. Transmittance of the structure

In order to investigate the origin of the red shift and the relation to quantum Stark effect, we have solved self-consistently the Schrödinger and Poisson equations by using the photogenerated electron and hole density (which are related to the optical power) as input parameters. The self-consistent procedure can be summarized as follows. Starting from the electron and hole density we first define the quasi Fermi levels. We than solve Poisson's equation and, from the obtained potential, we calculate the energy levels of the structure by solving the Schrödinger equation. At this point we recalculate the quasi Fermi levels iterate the procedure until convergence is achieved. This is a generalization to the non-equilibrium case of the self-consistent procedure used for electronic devices [6].

From the self-consistent solution of Schrödinger-Poisson equations in different conditions of optical CW injection, we found an unexpected low electric field that is not sufficient to modify the energy levels arrangement. There is, indeed, no strong accumulation of electrons into the reservoir R (large well) and holes into the well W (thin well). Thus, internal Stark effect seems to fail in justifying the deep red shift of transmittance spectra. An evidence comes from evaluation of the ratio of 2D densities in R and in W, as a function of optical pumping intensity: n_W^{2D}/n_R^{2D}, where $n_{R(W)}^{2D} = \int n^{3D}(x)dx$ is the integration along the growth axis and extends to the R (W) region.

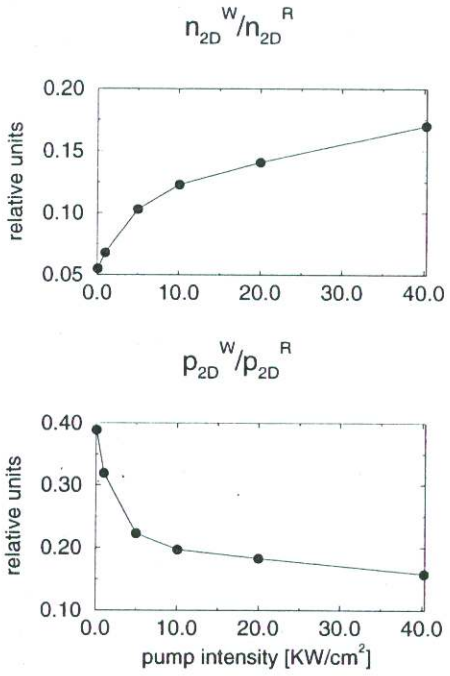

FIG. 3. 2D density ratio between well W and R

As clearly shown in Fig.3, the charge separation reduces with increasing intensity. Indeed, by increasing the optical power one can find more and more electrons inside the well W rather than in the reservoir R, and the opposite for the holes. In other words, by increasing the optical power the charges tends to distribute themselves uniformly over the whole structure.

In order to give a complete description of carrier behaviour we also considered temperature and gap renormalization effects.

To account for the device heating under the strong pumping intensities, we considered energy gap variations due to temperature according to the equation [7]:

$$E_{gap}(T) = E_{gap}(300) + T_{lin}(T - 300) + T_{quad}(T - 300)^2 \quad (1)$$

where $T_{lin} = -3.26 \cdot 10^{-4}\ eV/K$, and $T_{quad} = 3.31 \cdot 10^{-7}\ eV/K^2$.

We completed the description considering renormalization of the energy gap. Energy screening effects due to Coulomb interaction between electron and holes is thought to occur at densities as high as those available under heavy pumping conditions. Renormalization has two contributions: Coulomb-hole self energy, and exchange self energy between electrons. Tab.1 shows calculated [8] band gap narrowing.

Energy gap narrowing: renormalization and temp. contributions				
	W	R	Temp.	Intensity
A	−2.89 meV	−2.95 meV	300 K	0.01 KW/cm^2
B	−11.22 meV	−11.68 meV	300 K	0.1 KW/cm^2
C	−28.15 meV	−30.12 meV	310 K	5 KW/cm^2
D	−38.66 meV	−41.49 meV	323 K	10 KW/cm^2
E	−51.17 meV	−54.50 meV	340 K	20 KW/cm^2
F	−66.91 meV	−69.56 meV	420 K	40 KW/cm^2

Tab.1: Band gap narrowing

Within this complete model we found good agreement between calculated and experimental transmittance spectra, as one can see from Fig.4. Differences still exist due to excitonic peaks that are not considered in our calculations.

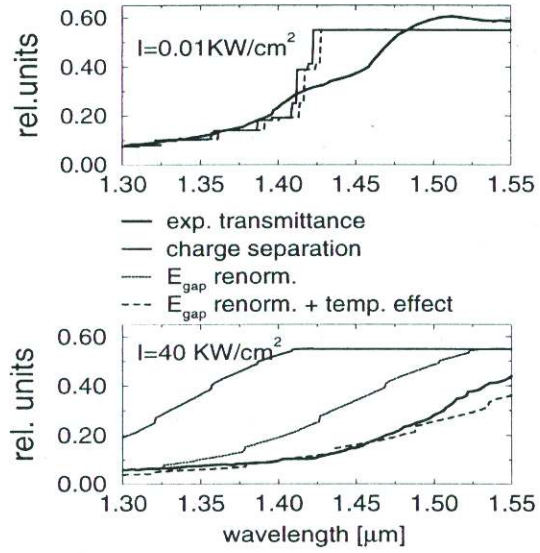

FIG. 4. Experimental vs. calculated transmittance for two different optical intensities.

It has been possible to apply our model to investigate highly non-equilibrium conditions. We considered non uniform quasi Fermi levels along the growth axis, corresponding to a situation of strong charge separation, i.e. heavily degenerated electrons and almost no holes inside the well W and vice-versa for the reservoir R. We found the interesting fact that absorption (and so transmittance) has a steplike behaviour with intensity. This is due to the appearance of a second quasi-localized energy level [9] inside the conduction band of W well at densities greater or equal than 5 KW/cm^2; this level brings a new contribution to optical matrix element, and changes transmittance spectra.

III. DYNAMICAL RESPONSE

Time domain simulations of the device are of fundamental importance in order to give a description of the nanostructure performance as an optical switch. The model developed to study the dynamical response is based on the picture of laser dynamics as obtained by mean of rate equations [10]. In the following, we consider separated dynamics for electrons and holes. This allows us to give a good description of the dynamical response of the device to a sequence of light pulses and to optimize the structure evaluating the effects of the various recombination mechanisms. The model considers several energy levels for electrons in the conduction band and holes in the valence band, one for each well, W and R (see Fig. 5)

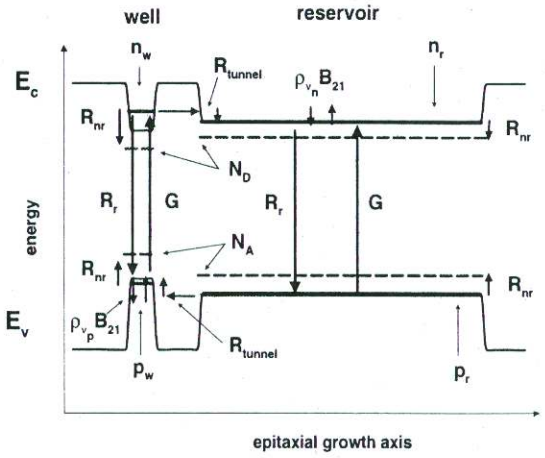

FIG. 5. Dynamic study of carrier concentrations: 4 level model

The set of differential equations describing the time evolution of carrier density can be written, according to Fig.5, as follows:

$$\begin{cases} \frac{\partial n_W}{\partial t} = G - \rho_{\nu_n} B_{21}(n_W - n_R) - R^n_{tunn} - R_{nr} - R_{rad} \\ (a)\ \textit{electrons in well } W \\ \frac{\partial n_R}{\partial t} = G + \rho_{\nu_n} B_{21}(n_w - n_R) + R^n_{tunn} - R_{nr} - R_{rad} \\ (b)\ \textit{electrons in } R \\ \frac{\partial p_W}{\partial t} = G - \rho_{\nu_p} B_{21}(p_W - p_R) + R^p_{tunn} - R_{nr} - R_{rad} \\ (c)\ \textit{holes in } W \\ \frac{\partial p_R}{\partial t} = G + \rho_{\nu_p} B_{21}(p_W - p_R) - R^p_{tunn} - R_{nr} - R_{rad} \\ (d)\ \textit{holes in } R \end{cases}$$

where the single terms have the following expressions:

$$G = \frac{1 - \mathbf{R}}{l_{cell} N_p} \frac{\mathbf{I}}{h\nu}$$

$$R_{tunn}^{n,p} = \begin{cases} A_{21} \cdot n_W = \frac{1}{\tau_{tunn}} \cdot n_W & \text{in c. band} \\ A_{21} \cdot p_R = \frac{1}{\tau_{tunn}} \cdot p_R & \text{in v. band} \end{cases}$$

$$\rho_{\nu_n} B_{21} = A_{21} / \left(e^{h\nu_n / KT} - 1 \right)$$

$$where\ A_{21} = \frac{1}{\tau_{tunn}^{CB}},\ \nu_n = (E_W^{CB} - E_R^{CB})/\hbar$$

$$\rho_{\nu_p} B_{21} = A_{21} / \left(\exp^{h\nu_p / KT} - 1 \right)$$

$$\text{where } A_{21} = \frac{1}{\tau_{tunn}^{VB}},\ \nu_p = (E_W^{VB} - E_R^{VB})/\hbar$$

$$R_{nr} = \begin{cases} n_W/\tau_{nr} & \text{in c. band of well W} \\ n_R/\tau_{nr} & \text{in c. band of well R} \\ p_W/\tau_{nr} & \text{in v. band of well W} \\ p_R/\tau_{nr} & \text{in v. band of well R} \end{cases}$$

$$R_{rad} = \begin{cases} r \cdot n_W p_W & \text{in well W} \\ r \cdot n_R p_R & \text{in well R} \end{cases} \qquad (2)$$

In the above expressions we assumed the reflectivity $\mathbf{R} = 0.3$, the number of periodic cells $N_p = 30$, the incident photon energy $h\nu = 1.165\ eV$, the length of periodic cell $l_{cell} = 954$ Å, the tunneling times $\tau_{tunn}^{CB} = 1\ ps$, $\tau_{tunn}^{VB} = 10\ ps$ and the radiative recombination constant $r = 10^{-10}\ cm^{-3}s^{-1}$. For the non radiative time constant we considered two values: $\tau_{nr} = 100\ ns$ (undoped sample) and $\tau_{nr} = 1\ ps$ (doped sample) [11]

This picture allow us to consider the dynamic of charge redistribution, starting from radiative recombination, and considering also thermionic emission from the deeper energy level into the higher one. At the same time the model considers the tunneling rate across the barriers separating the wells W and R, with corresponding relaxation to the deeper energy level. The inclusion of non-radiative recombination accounts for all possible modification of the device performance induced by heavy doping.

With this set of rate equations it has been possible to compare the dynamic performances of the ACMQW structure (where radiative recombination is dominant), with an heavily doped ACMQW structure ($N_A = N_D \geq 10^{18}$) where non radiative capture by defects or traps is the dominant recombination rate. We have found that in order to optimize the structure (best switching performance) is necessary to introduce high concentrations of centers for non recombination capture.

Fig.6 shows the saturation time of carrier concentrations as a function of the pumping rate. Here, the saturation time is the time needed to reach stationary condition.

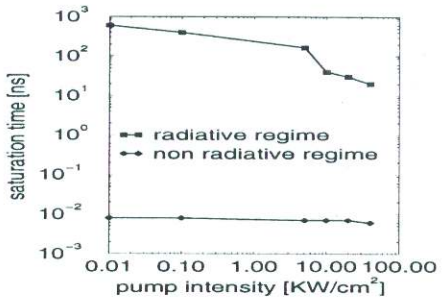

FIG. 6. Saturation time for carrier concentrations

IV. CONCLUSIONS

A model of an optical switch based on asymmetric double quantum wells has been presented. Our theoretical study has led to the understanding of the factors determining the strong non linearity observed in experiments on fabricated devices. Band gap renormalization seems to be essential to explain the big red shift of sample transmittance; Dynamical simulations in radiative regime have shown the feasibility of switching operation only under heavy pumping conditions ($> 7 \cdot 10^{12}$ cm^{-2}) and at a maximum bit rate of 100 Mbit/s. Instead, in the non radiative regime (heavily doping to obtain fast recombination centers), we have shown the possibility to deeply modulate photoexcited carrier concentration under any pump condition at very high pulse train frequency (up to 10^{11} Hz).

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