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Performance prediction of an electroabsorption modulator at 1550 nm using GeSn/SiGeSn Quantum Well structure

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HIGHLIGHTS

- ► Absorption spectra in strain-free $Ge_{0.992}Sn_{0.008}/Si_{0.3}Ge_{0.61}Sn_{0.09}$ Quantum Well is reproduced.
- ► Two Gaussian distributions for heavy hole and light hole excitons and the Sommerfeld factors are used.
- ► The expressions are then used to obtain the change in refractive index, Δn, with field.
- ► Performance parameters like extinction ratio, chirp parameter, and a figure of merit are evaluated.
- ► The best value of bias voltage that makes the sum of derivatives of T with V equal to zero is evaluated.

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ABSTRACT

The absorption spectra in strain-free $Ge_{0.992}Sn_{0.008}/Si_{0.3}Ge_{0.61}Sn_{0.09}$ Quantum Well structure due to direct gap excitons formed in $Ge_{0.992}Sn_{0.008}$ wells reported by Chang and Chang are reproduced by an empirical expression. Two Gaussian distributions for heavy hole and light hole excitons and two exponential functions describing continuum transitions and The Sommerfeld factors are used for the fit. The expressions are then used to obtain the change in refractive index, Δn, with field (electrorefraction) using the Kramers–Kronig relation. With the calculated changes in absorption and refraction with bias, other performance parameters of an Electro-Absorption Modulator (EAM), like extinction ratio, chirp parameter, and a figure of merit (FoM) defined as the ratio of extinction coefficient and insertion loss, are evaluated. The FoM takes the largest value for 1 μm length of the EAM with 2 V bias applied to the p–i–n structure. The parameters are also calculated for different wavelengths as well as detuning lengths. For applications as short pulse generation the transmission T as a function of bias V should be linear. We have evaluated the best value of bias voltage that makes the sum of second and third derivatives of T with V equal to zero so that the variation of T with V becomes maximally linear for optimum operation as a short pulse generator.

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1. Introduction

Over the last few decades a lot of research has been conducted to achieve efficient light emission and high speed modulation from Si and its alloys either in bulk form or quantum heterostructures made by Si-based materials [1,2]. The indirect band gap of silicon makes the probability of light emission extremely low. At the same time the long recombination lifetime of excess electron–hole pairs in Si based structures is responsible for poor modulation bandwidth. Quantum nanostructures using Si and its alloys have been extensively studied by workers to improve the light emission efficiency [1,2]. In the area of modulators, the absence of linear electro-optic effect in Si led researchers to use devices and structures different from the III–V semiconductor counterparts [3–8]. Most of the Si based modulators rely on the injection of electrons and holes into an active region by an electric bias. The preferred device has been a p–i–n diode, or a MOS capacitor in which the excess carriers injected into the i region change the refractive index of the material [5,6]. The phase modulation achieved is then converted into intensity modulation by using a Mach Zehnder configuration. By novel design the modulation bandwidth of the devices could be made as high as 40 GHz or so [7]. The dimensions could be reduced to even a few micrometer and the whole structure can be grown on Si substrate by using standard CMOS technology [8].

The modulators currently being used in optical fibre communication links are electroabsorption modulators (EAMs) made of InGaAsP/InP Multiple Quantum Wells (MQWs) [9]. The operation of the device is based on Quantum Confined Stark Effect (QCSE) [10] in which an external electric field shifts the excitonic absorption spectra. The MQW forms the intrinsic (i) region of a p–i–n structure. By changing

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the bias, the absorption or transmission of light at a fixed wavelength can be changed, thus accomplishing intensity modulation.

There have been several attempts to observe QCSE in Si and its heterostructures; however no encouraging results were obtained. Kuo et al. [11–13] observed for the first time strong QCSE in Ge–Si MQWs in which the strain distribution is made symmetric by using a suitable SiGe buffer layer. They later reported encouraging results for modulators using this phenomenon. The strong QCSE arises due to transition from light hole (lh) and heavy hole (hh) subbands to the direct conduction subbands in Ge wells (Γ valley). However, due to 4% lattice mismatch between Si and Ge, growth of Ge wells on a Si substrate via a SiGe buffer induces a biaxially compressive strain in the Ge well. This strain and QW confinement energy increase the excitonic transition energy of the Ge wells from their unstrained direct band gap of 0.8 eV. As a result, the wavelengths of optimal extinction ratio in their structure are in the 1440–1460 nm range. Recently, Chang and Chang [14] proposed a strain-free $Ge_{0.992}Sn_{0.008}$/$Si_{0.3}Ge_{0.61}Sn_{0.09}$ QW structure to develop an EAM at 1550 nm. They estimated an optimal well width of 11–12 nm to achieve a high absorption contrast up to 4.41 for high performance EAMs.

In addition to their use as modulators in telecommunications at around 1550 nm, EAMs also find applications in various other areas, an example being narrow pulse generation [15,16].

In the present work we propose to estimate several other parameters of EAMs like extinction ratio (ER), chirping parameter and the insertion loss using the reported values of both TE and TM absorption in $Ge_{0.992}Sn_{0.008}$/$Si_{0.3}Ge_{0.61}Sn_{0.09}$ QW structure. For estimation of such parameters the values for electrorefraction, i.e., change in refractive index of the structure with electric field is an essential parameter. Here, we have used a simple procedure developed in our earlier work [10]. We first fit the absorption spectra reported by Chang and Chang [14] by using an empirical relation. Then using the calculated values of the change of absorption $\Delta\alpha$ with the field, we obtained the values of Δn, the change in RI, by using Kramers–Kronig relationship [17,18]. The values of $\Delta\alpha$ and Δn are then used to calculate chirping parameters, extinction ratio, etc. We have also attempted to optimize several performance parameters of EAMs by using the reported absorption spectra and our results derived through the above analysis.

2. Theory

Chang and Chang [14] reported the QCSE in strain free $Ge_{0.992}Sn_{0.008}$ QW with $Si_{0.3}Ge_{0.61}Sn_{0.09}$ barriers. A schematic of the structure used by them is shown in Fig. 1. The well width is 11 nm and the barrier width is set at 10 nm for moderate excitonic absorption. They reported the TM and TE absorption spectra without electric field as well as with fields in the range $2-12$ MV/m with 2 MV/m steps.

We have used a simple procedure to reproduce the reported absorption spectra, which has been prescribed in Ref. [10] in connection with excitonic electroabsorptions in GaAs–AlGaAs QWs and then applied in Ref. [17] for the Ge–Si MQW structure studied by Kuo et al. [11]. In this method the sum of two Gaussian distributions and a broadened two dimensional (2D) continuum is used to fit the curves. To describe the absorption at room temperature we have used the following expression [17] that takes into account two discrete excitonic transitions (hh-e, and lh-e) as well as absorption by the 2D continuum states:

$$\alpha(\hbar\omega)=\alpha_{\mathrm{h}}\exp\left[-\frac{(\hbar\omega-\hbar\Omega_{\mathrm{h}})^2}{2(\hbar\Gamma_{\mathrm{h}})^2}\right]+\alpha_{\mathrm{l}}\exp\left[-\frac{(\hbar\omega-\hbar\Omega_{\mathrm{l}})^2}{2(\hbar\Gamma_{\mathrm{l}})^2}\right]+\frac{\alpha_c}{1+\exp(\hbar\Omega_{\mathrm{c}}-\hbar\omega/\hbar\Gamma_{\mathrm{c}})}\frac{2}{1+\exp\{2\pi[\hbar\Omega_{\mathrm{c}}-\hbar\omega|/R_y]^{-1/2}\}} \tag{1}$$

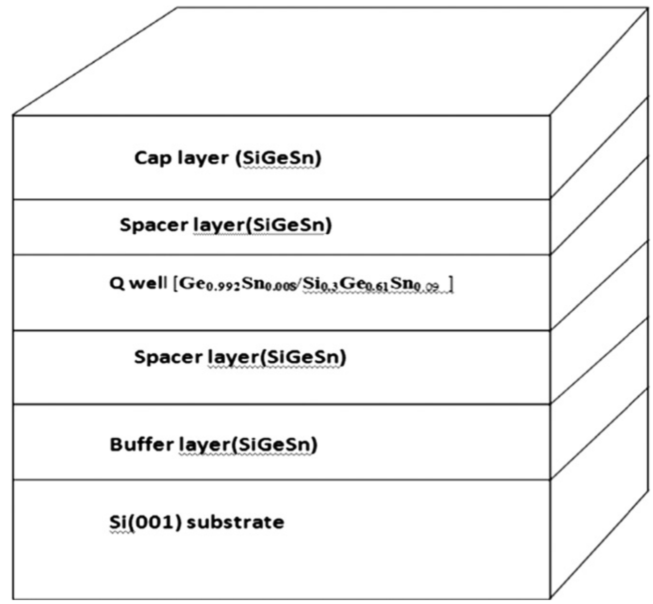

Fig. 1. Quantum Well structure.

where $\hbar\omega$ is the photon energy, $\hbar\Omega$ denote the excitonic peak energy width, Γ's represent the linewidths (HWHM), α's are fitting parameters, R_y stands for exciton Rydberg and subscripts h, l and c correspond, respectively, to hh, lh and continuum states. We have not included separately the two different continuum contributions from the hh and lh subbands.

The agreement between reported curves and the values calculated with suitable chosen parameters is excellent as will be illustrated in the next section. Having reproduced the absorption spectra for different field values, the change in refractive index or electrorefraction, Δn, is calculated using Kramers–Kronig integral

$$\Delta n(E,F)=\frac{c\hbar}{\pi}\int_0^{\infty}\frac{\alpha(E',F)-\alpha(E',0)}{E'^2-E^2}dE' \tag{2}$$

where $E=\hbar\omega$ is the transition energy at which Δn is calculated and $\alpha(E,F)$ is the absorption coefficient at energy E and field F. The change in extinction coefficient Δk is obtained from the relation [18,19]

$$\Delta k(E,F)=\frac{\lambda}{4\pi}[\alpha(E,F)-\alpha(E,0)] \tag{3}$$

where λ is the wavelength corresponding to transition energy E.

The performance of an EAM depends on several basic parameters which include extinction ratio (ER), amount of detuning of the operation wavelength from the exciton absorption peak, insertion loss (IL) and the chirping parameter (α_{chirp}).

All these parameters are expressed by the following equations:

$$ER\ (\text{in } dB)=4.343\ [\alpha(E,F)-\alpha(E,0)]\Gamma_{qwi}L \tag{4}$$

$$\alpha_{\mathrm{chirp}}=\frac{4\pi}{\lambda}\frac{\Delta n(E,F)}{\Delta\alpha(E,F)}, \tag{5}$$

and

$$IL=1-\exp\lfloor-\alpha(E,0)\Gamma_{\mathrm{qwi}}L\rfloor \tag{6}$$

where L is the length of the modulator and Γ_{qwi} is the optical confinement factor of quantum well [20] given by,

The modal absorption is calculated by multiplying the material absorption by

$$\Gamma_{\mathrm{qwi}}=t_{\mathrm{qwi}}/\left(t_{\mathrm{tot}}+\frac{2}{t_{\mathrm{ot}}(\varepsilon_{\mathrm{a}}-\varepsilon_{\mathrm{b}})}\sqrt{\frac{\varepsilon_e}{\varepsilon_{\mathrm{qwi}}}}\left(\frac{\lambda}{2\pi}\right)^2\right) \tag{7}$$

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