Modulation Doped SiGe–Si MQW for Low-Voltage High-Speed Modulators at 1.3 μm

Adrian Vonsovici and Lili Vescan

***Abstract*— We propose a new type of light modulator at 1.3 and 1.55 μm using a δ–modulation-doped SiGe–Si multiple-quantum-well structure (δ-MDMQW) integrated in a low-loss silicon-on-insulator (SOI) waveguide. The structure is embedded in the intrinsic region of a vertical p-i-n diode realized on SOI substrate. We present theoretical calculation of the effective index modulation determined by the variation of the confined hole concentration with an applied external field. A practical device is proposed and a calculation of optical modulation efficiency is presented. Estimation of on–off switching time based on evaluation of characteristic time of emission from localized levels in quantum wells and *RC* characteristics of the device are presented.**

This device presents the advantage of a broad optical bandwidth in comparison to the modulators based on quantum-confined Stark effect, low insertion loss, high-speed (above 1 GHz), and full compatibility with silicon technology.

***Index Terms*— Charge transfer devices, electrooptic modulation, integrated optoelectronics, optical strip waveguide components, phase modulation, quantum-well devices, silicon-on-insulator technology.**

I. INTRODUCTION

THE REALIZATION of optoelectronic devices based on SiGe–Si heterostructures has been proposed by several authors [1], [2]. Efforts of the researchers are concentrating mainly on detectors and photoreceivers, but recently there have been several attempts of proposing light emitters [3] and modulators [4]. Si-based light modulators using large rib silicon-on-insulator (SOI) have been proposed and realized [5]. For these devices, the modulation with a bandwidth of a few megahertz is obtained using the electrorefractive effect associated with the bipolar carrier injection in the core of a SOI waveguide. Even if there are promising results in this direction there is still a challenge to realize high-speed optical modulators at 1.3 and 1.55 μm compatible with the silicon technology.

The high-speed regime could be attained if we use SiGe–Si heterostructures either using type-II QW or the quantum-confined Stark effect (QCSE) [6], but this type of modulators is very difficult to realize in practice. A SiGe–Si type-I QW exhibits a very low Stark effect as demonstrated in [7]. Recent calculation of indirect band-to-band absorption and electrooptic effect in SiGe–Si QW has shown that it is possible to obtain relatively large ($\Delta\alpha \approx 75$ cm^{-1}) absorption modulation but this type of modulator will have a very narrow optical bandwidth (like any other Stark effect based modulators) [8]. Also it seems that this value must be reconsidered as up to now SiGe–Si MQW waveguides have confinement factors less than 0.05–0.1 in active region and not 1 as the authors mistakenly considered. Also, due to the very low exciton binding energy sensitivity with temperature will be a serious problem. In principle, the speed limitation can also be overcome by using a heterostructure in which only a unipolar carrier injection is used to achieve refractive index modulation.

A broad optical bandwidth modulator will take into account an electrorefractive effect in the transparent region of the SiGe alloys. An interferometer structure (Mach–Zehnder) will transform the induced phase modulation in amplitude modulation. At this moment there is no experimental report of the electrorefractive or electroabsorption effects in SiGe multiple quantum wells. Also, there is no reported measurement of refractive index or extinction changes associated with the two-dimensional (2-D) hole gas confined in a SiGe–Si modulated-doped quantum well. As for this type of system we could vary the concentration of confined holes by an external applied field a new type of electro-optic devices could be envisaged. Such a carrier transfer structure (CTS) could operate at high-speed regimes as it is no more limited by the carrier recombination times but by the escape of the carriers from confining quantum wells (with a characteristic time in the range 10–100 ps).

It is the purpose of this paper to analyze a charge (hole) transfer electrooptic modulator, which could be made using δ–modulation-doped SiGe–Si multiple quantum wells embedded in the intrinsic region of a p-i-n diode.

The free-carrier effect based modulators operate in a high-injection regime with a very poor frequency characteristic [5]. The current versus voltage (I–V) characteristic of a p-i-n Si diode used for free-carrier injection and the shape of the external modulation bias is depicted in Fig. 1(a). In the absence of a forward bias or for small forward biases there is no significant charge density in the intrinsic region of the p-i-n diode. The diode must be dc-biased, corresponding to a current density of about 100 A/cm^2 to ensure a significant carrier concentration ($\sim 10^{16}$ cm^{-3}). An ac signal superposed to this could insure the switching between two levels of stored charges in the central region of the p-i-n diode. This is the main technique to obtain a significant refractive index modulation of this region.

The numerical simulations [9] show that operation at 100 MHz is feasible without any parasitic thermal effects. We must notice that this switching mechanism is used also for

Manuscript received April 13, 1998; revised July 1, 1998.

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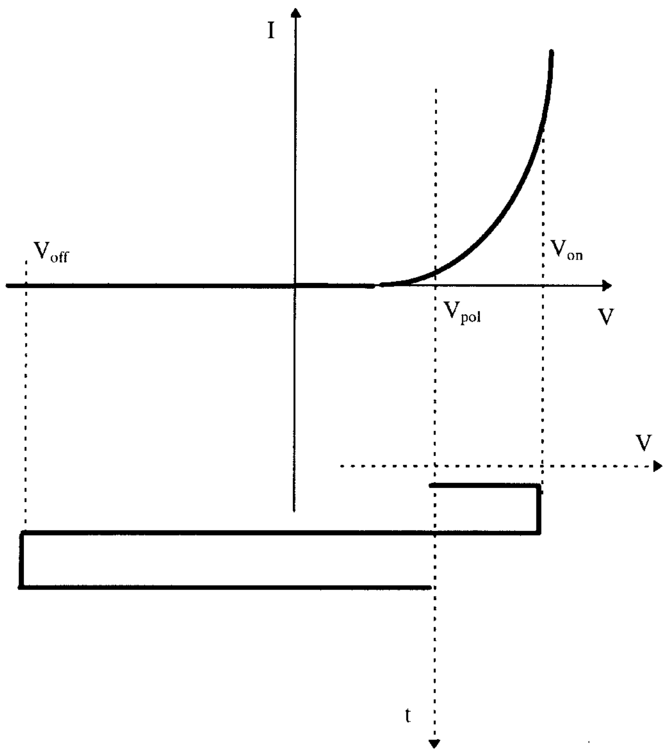
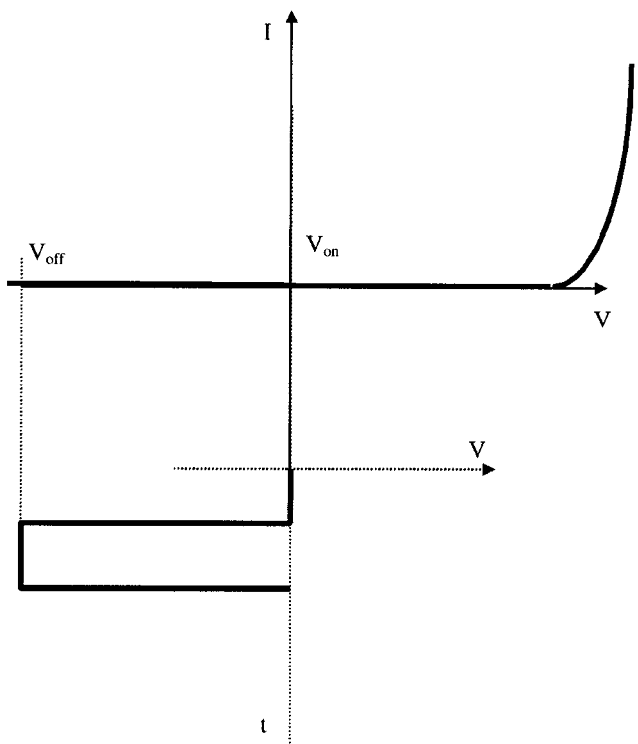
Publisher Item Identifier S 1077-260X(98)08601-8.



(a)



(b)

Fig. 1. (a) Principle of operation on an I–V characteristic for a Si-based optical modulator. A steady state bias corresponding to a relatively high injected current is necessary to achieve a few hundred megahertz modulation bandwidth. (b) Principle of operation on the I–V characteristic for a charge transfer structure. The overall current in the device is significantly reduced.

microwave Si p-i-n diodes. The main disadvantage is the high static polarization current in the device and thermal effects associated with this. This problem could be solved for discrete devices but it is very difficult to give a solution for monolithic devices on a silicon-on-insulator substrate.

A carrier transfer structure based modulator will switch between two states with different carrier concentrations in the central region of a p-i-n diode without a significant steady-state current passing through the device. The reason is that an important confined charge could be stored even in the absence of an external bias for a modulation-doped multiple quantum well structure. If a reverse bias is applied on the diode, the high electric field will rapidly evacuate the stored charge (holes in the case of SiGe–Si QW) from the central region. The expected I–V characteristic and the bias pulse for the on–off switching of the device are shown in Fig. 1(b).

As compared to carrier injection operation, this device has the important advantage of voltage controlled operation with low power dissipation and a time response governed by *RC* time constant and the time constant for hole escape from the quantum well.

The efficiency of a refractive index modulation must be evaluated for a given waveguide geometry where an effective index modulation is realized in the waveguide core. This is an important aspect of a modulator design. Searching for important refractive index modulation some authors [8] neglected the important problem of the confinement factor in the region where the refractive index modulation occurs. This is a key parameter for an optical modulator.

For SiGe–Si heterostructure waveguides, the main problem is the critical thickness for plastic relaxation of the SiGe layer that could be realized in practice. This is usually less than 0.1 μm for SiGe alloys with more than 20% of Ge. Therefore, for a waveguide geometry with the guiding layer more than 1 μm thick, the confinement factor in the SiGe layer will be reduced to less then 0.1. This implies that for a modulator with a length less then 5 mm a modulation of refractive index between $5 \cdot 10^{-4}$ and 10^{-3} will be necessary to achieve 180° phase modulation at 1.3 μm. For this purpose, carrier concentrations in the range 2–$5{\cdot}10^{17}$ cm^{-3} are necessary.

A depletion mode Si p^+-i-p-i-n^+ structure could operate using the same principle of operation as the SiGe–Si p^+-i-(MQW)-i-n^+ diode. However, for the Si diode the p-region has an antiguiding effect. It is well known that a Si-doped region has a lower index than the intrinsic Si regions so the active region will have a slightly lower refractive index. Nevertheless, this could be a new version of a depletion mode Si-based modulator. Using the SiGe–Si MWQ structure we have some advantages.

1) The MQW region provide a strong confinement of the light in the active region due to the higher refractive index of the SiGe ($n_{\mathrm{SiGe}} = 3.55$ for 20% Ge).
2) The expected free-carrier effect in SiGe alloys is theoretically superior to that in Si due to smaller effective mass of the holes in these alloys.
3) A SiGe–Si MQW region will improve also the series resistance of the diode reducing the leakage current for a given bias.
4) Using the SiGe–Si MQW we have the possibility to integrate the modulator with a SiGe based MODFET's for high-speed operation.

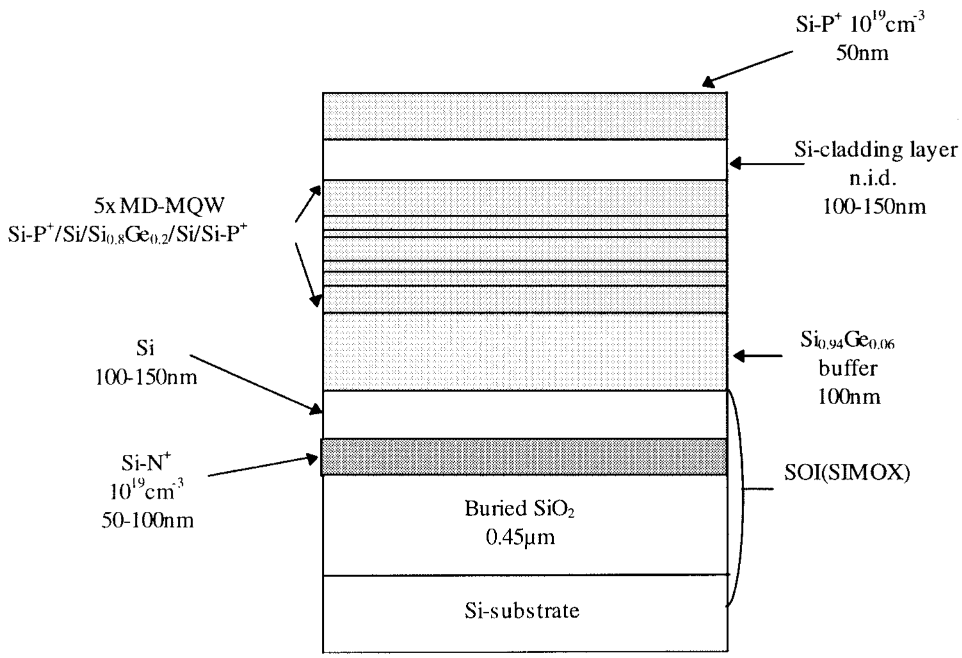


Fig. 2. Proposed structure of the δ–modulation-doped MQW modulator. The structure is made using an SOI substrate to increase the optical guided mode confinement in the active region. The structure has five periods of modulation-doped SiGe–Si QW.

A significant progress for SiGe–Si heterostructures has been obtained by using the selective epitaxy. This allows thicker strained SiGe layers to be grown as compared to large area deposition as demonstrated in [10]. A vertical p-i-n structure could be realized by this method on a SOI substrate and the oxide walls used for the localized growth would insure both the diode passivation and lateral optical confinement. One of the original aspects in this proposal is that the 2-D guiding structure could be defined not by etching a rib but by selective epitaxy in predefined etched grooves. This could avoid rib etching and subsequent oxide deposition for passivating the etched walls as for classical rib-structure modulators.

The paper is organized as follows. After Section I, we present the device structure and the principle of operation. In the Section III, the theoretical model for a SiGe–Si δ modulation-doped double-heterostructure quantum well is described. Calculations of the confined hole concentration have been carried out for an applied external electric field. This allowed us to evaluate the electrorefraction corresponding to these hole concentration variations.

In Section IV, the optical simulation results are presented. The intrinsic region of the p-i-n diode contains several SiGe–Si δ modulation-doped double-heterostructure quantum wells. The expected effective index modulation for the fundamental guided mode is calculated. An analysis of the switching characteristic of the structure is presented. The main mechanism that limits the modulation speed is the time of emission over the barrier of the confined holes. The device uses unipolar carrier injection so the operation is not governed by recombination mechanisms as it is the case for injection p-i-n Si modulators but by thermionic emission of confined holes over the potential barrier and *RC* time constants. Finally, the conclusions are drawn in Section V.

II. Modulator Structure and Principle of Operation

We depicted in Fig. 2 the schematic of the proposed modulator. In principle, it consists of a vertical p-i-n diode grown on top of a silicon-on-insulator substrate (SIMOX). First the substrates are implanted to form a n^+ buried layer (50–100 nm thick) on the bottom of the diode structure. This allows us to realize a lateral contact to the n^+ region of the diode. Next, we realize the waveguide p-i-n structure by selective epitaxy. For that a silicon dioxide oxide layer is deposited and using reactive ion etching we define the grooves where the epitaxy will be performed. First, an undoped buffer layer is grown to insure a good quality for the SiGe strained layers. The thickness for this region is in the range 100–300 nm as demonstrated by preliminary experimental results in [3]. Five δ–modulation-doped double-heterostructure quantum wells are grown on top of the buffer. This region forms the active region of the modulator where the refractive index modulation will occur. The active region is cladded by an undoped region and the top p^+ layer with a thickness of 50–100 nm. The thickness of the cladding layer will be adjusted to insure a good overlap of the optical mode with the modulated refractive index region. The doping of the n^+ and p^+ (contact) layers is taken $5 \cdot 10^{18}$ cm^{-3} and the $\delta - p^+$ layers have a doping in the range 2–$3 \cdot 10^{18}$ cm^{-3}.

In the absence of an external electric field, the holes are transferred from the adjacent $\delta - p^+$ regions and confined into the quantum wells. By applying a reverse bias, the strong electric field evacuates the holes toward the adjacent contact. The two states have different confined hole concentrations that will determine a modulation of the refractive index of the region. The SOI structure allows a strong confinement for an optical guided mode and a good superposition with the active region. The guided mode effective index modulation will be

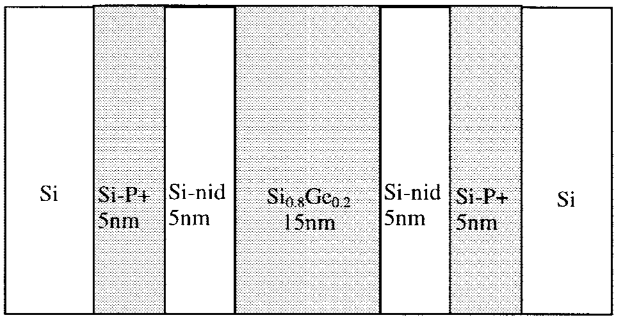


Fig. 3. Schematic of a δ–modulation-doped QW used as a building block for the modulator.

calculated in the following sections using the concentration of the confined holes and the optical waveguide simulations.

III. SiGe–Si δ–Modulation-Doped Double Heterostructure

The schematic of only one δ-doped modulation-doped quantum well is presented in Fig. 3. It consists of a $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ δ-doped quantum well 15 nm large. The two $\delta - \mathrm{p}^+$ regions are 5 nm thick and are separated by undoped Si barriers of 5 nm.

Since the charge distribution in the structure also modifies the quantum well potential we need a self-consistent solution of Schrödinger's wave equation and Poisson's equation. Assuming a slowly varying effective mass, a Ben–Daniel–Duke Hamiltonian is used [11]:

$$\left(-\frac{\hbar^2}{2m_0}\frac{d}{dz}\left(\frac{1}{m(z)}\frac{d}{dz}\right)+E_V(z)\right)\Psi_i(z)=E_i\Psi_i(z) \quad (1)$$

where $m(z)$ is the hole effective mass, E_i is the energy level in the quantum well, and Ψ_i is the hole wavefunction. The Poisson's equation has the form

$$\frac{d^2\Phi}{dz^2}=-\frac{q}{\varepsilon_0\varepsilon}\left(N_D-N_A+p-n\right) \quad (2)$$

where ε is the relative permitivity, Φ the electrostatic potential, q the electron charge, p and n the concentrations of free holes and electrons and N_D and N_A the doping concentrations.

The potential energy in the Schrödinger's equation contains the band offset at the heterointerfaces ΔE_V and the electrostatic potential Φ:

$$E_V(z)=q\Phi+\Delta E_V(z). \quad (3)$$

After the discrete energy levels E_i and wavefunctions Ψ_i are determined the hole density in the QW, assuming a 2-D density of states, is given by [11]:

$$p(z)=\sum_i \frac{m_h k_B T}{\pi\hbar^2}\cdot\ln\{1+\exp[(E_F-E_i)/k_BT]\}|\Psi_i|^2 \quad (4)$$

where k_B is Boltzmann's constant, T is the temperature, m_h is the hole effective mass and E_F is the Fermi energy. For bulk layers, carrier densities are given by the classical Fermi–Dirac statistics expression:

$$p=N_V\frac{2}{\sqrt{\pi}}F_{1/2}\left(\frac{E_V-E_F}{k_\mathrm{B}T}\right) \cong \frac{N_V}{0.25+\exp\left(\frac{E_F-E_V}{k_\mathrm{B}T}\right)}. \quad (5)$$

We used a finite difference method with a nonuniform mesh [12] to solve (1) and (2) self-consistently. This allowed us to take into account precisely the regions where the wave function varies rapidly and in the same time to reduce the number of mesh points in the regions where no significant change in the wave-function is present. The method is employing a matrix transformation to preserve the symmetry of the finite-difference Schrödinger's equation and the Newton method to solve the Poisson's equation.

The boundary conditions used for the electrostatic potential are:

- in the bulk ($z=z_{\mathrm{end}}$), $\Phi=0$, and $d\Phi/dz=0$
- at the surface ($z=0$) $\Phi=\Phi_0$ (a given electrostatic voltage drop across the structure).

The initial voltage profile was taken to be the flat-band condition with the valence-band discontinuity at the SiGe–Si interface. The mol fraction x of $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ was assumed to be 0.2 (bandgap discontinuity ~0.17 eV [13], [14]) and the doping of the δ-doped regions was assumed between 2 and $3\cdot10^{18}$ cm^{-3}. The residual doping density in the Si barriers and the other nonintentionally doped regions was assumed to be 10^{15} cm^{-3}. We depicted in Fig. 4 the results obtained for the confined hole concentration for the 0-V bias and for a reverse bias of -1 V. The corresponding valence band energy diagram for the two states was also shown in Fig. 5. For the 0-V state a confined hole gas is present at the two interfaces and the average concentration is relatively important. The transferred charge from the δ–p$^+$ regions to the quantum-well depends on the barrier thickness. A 5-nm Si-barrier was sufficient to obtain more than 10^{18} cm^{-3} confined holes in the quantum well.

As we can see from the two graphs an important variation in the hole concentration confined in the quantum well, from about 10^{18} cm^{-3} to less than $2\cdot10^{16}$ cm^{-3}, takes place for a reverse bias of -1 V. This variation will lead to a significant modulation of the refractive index of the QW + barrier region. The average hole concentration confined in the quantum well decreases linearly with the external applied electric field as for any other modulation-doped double-heterostructure. For the -1-V bias voltage the corresponding electric field on the double-heterostructure is not exceeding 10^5 V/cm, which is inferior to the breakdown field of Si for a 10^{15} cm^{-3} doping ($4\cdot10^5$ V/cm).

IV. Optical Simulation Results and Discussion

In this section, we will calculate the effective index change for the proposed waveguide modulator in Fig. 1. The characteristic time of the effective index modulation is also evaluated. For the optical simulation, we supposed that the variation in absorption and refractive index of a SiGe alloy with varying

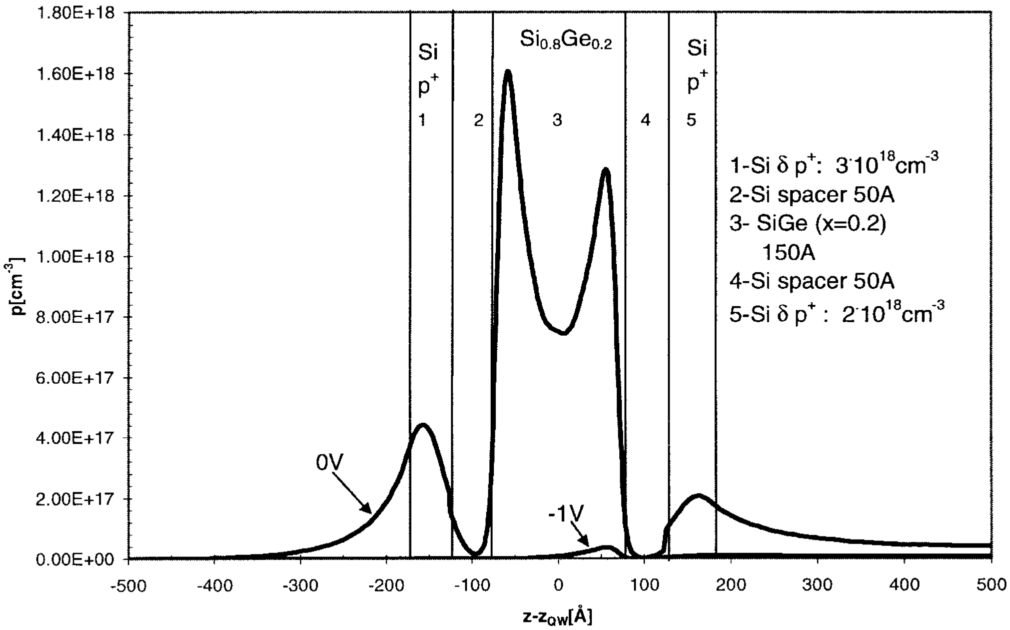


Fig. 4. The confined hole concentration in the SiGe QW (see Fig. 3) for zero bias and a reverse bias of -1 V, respectively. A significant amount of confined holes is present in the QW (10^{18} cm^{-3}) and could modify substantially the refractive index of the SiGe. For a reverse bias of -1 V the averaged confined hole concentration in the QW is reduced to less than $2 \cdot 10^{16}$ cm^{-3}.

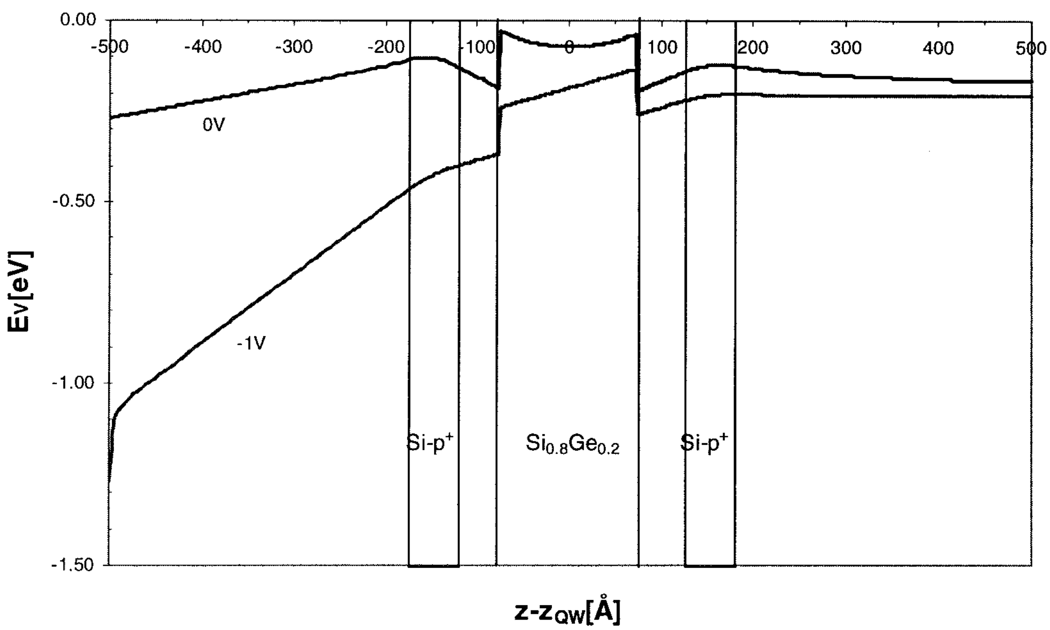


Fig. 5. The valence band energy diagram for the two bias voltages. The Fermi level E_F was taken as a reference.

carrier concentrations are described by a formula similar for 3-D free-carriers in silicon. This was imposed by the lack of experimental results for the free-carrier effects for strained SiGe alloys. Moreover, the electrorefraction associated with a given concentration of free-carriers in Si is inferior to that in Ge and for low concentrations of Ge we could suppose that $\Delta n(\mathrm{Si}) < \Delta n$(SiGe-unstrained) $\approx$ Δn(SiGe-strained) $< \Delta n$(Ge) [15]. This is a good approximation for Ge concentrations not exceeding 30% [15]. Also, for SiGe alloys we could use the classical Drude formula to calculate the electrorefraction associated with free-carriers that gives good results for Si and Ge. For a hole concentration in the range 10^{17} to 10^{18} cm^{-3} an electrorefraction 50% greater than that corresponding for silicon is obtained [15], [16].

Further experimental investigation is necessary but the exact magnitude for the free-carrier effect is very difficult to estimate even for Si as indicated by Soref [16]. Thus, we considered for our calculations the formulas obtained by Soref [16], [17] for Si which give us the lower limit for the effect. Introducing the exact values for the refractive index and the extinction coefficient changes in SiGe will just give greater values for the effective index modulation than that estimated further below.

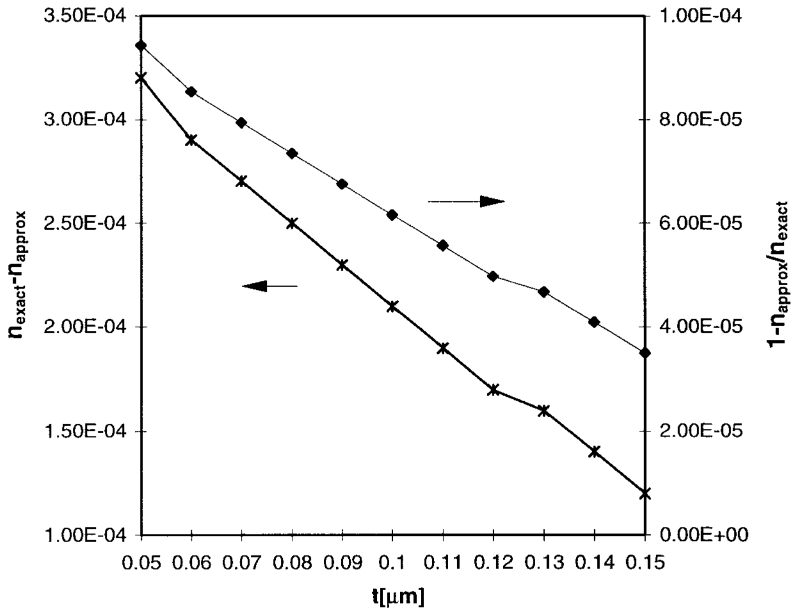


Fig. 6. Comparison between an exact multilayer algorithm using all the layers in the MQW region and a calculation using the multilayer algorithm with the MQW region replaced by an averaged refractive index. The figure shows the results for a Si cap layer with a thickness (t) in the range 50–200 nm. Minor differences are obtained for the effective index and confinement factors.

We considered for our calculations a TE polarization and a wavelength $\lambda = 1.3$ μm.

Our optical model takes into account the waveguide structure depicted in Fig. 2. A transfer-matrix method was used to calculate the effective index and the field intensity profile in the structure [18], [19]. Searching for an optimized structure we further used an approximation for the MQW region, currently used for the study of guided modes in MQW structures. This allows us to reduce the computational time without reducing the precision of our calculations. The field profiles and confinement factors are practically the same and the small differences in the effective index values are far less than that obtainable in practice due to tolerances in layer thicknesses.

The approximation used for the MQW region [20], [21] consists mainly in considering an average refractive index for the MQW region calculated for a TE polarization as

$$n_{\mathrm{TE}}^2 = \frac{\sum_j n_j^2 l_j}{\sum_j l_j} \tag{6}$$

where the n_j, l_j are the refractive indices and thicknesses of each layer in the MQW region.

The comparison with the exact values obtained using the multilayer algorithm in the MQW region is depicted in Fig. 6. The difference between the effective indices obtained using the two methods is represented as a function of Si cap layer thickness. The difference is negligible (less than $5 \cdot 10^{-4}$ in absolute value, the Si refractive index being known at 1.3 μm with a precision of 10^{-3}). The field intensity profile obtained is depicted in Fig. 7 for a Si capping layer of 110 nm. Using the first order perturbation theory the local refractive index change determines an effective index change for a waveguide mode given by [22]

$$\Delta n_{\mathrm{eff}} = \frac{1}{n_{\mathrm{eff}}^{(0)}} \cdot \frac{\int_{-\infty}^{\infty} \Delta n(z) \cdot n_0(z) |E^{(0)}(z)|^2 \, dz}{\int_{-\infty}^{\infty} |E^{(0)}(z)|^2 \, dz} \tag{7}$$

where $|E^{(0)}(z)|^2$ is the optical intensity profile, $n_0(z)$ is the refractive index distribution in the structure and $n_{\mathrm{eff}}^{(0)}$ is the effective index of the mode in the absence of modulation.

The local refractive index change with applied bias is significant only in the MQW region. Therefore the effective index change could be expressed as follows:

$$\Delta n_{\mathrm{eff}} = \frac{n_{\mathrm{TE}}}{n_{\mathrm{eff}}^{(0)}} \cdot \overline{\Delta n} \cdot \Gamma \tag{8}$$

where

$$\Gamma = \frac{\int_{\mathrm{MQW}} |E^{(0)}(z)|^2 \, dz}{\int_{-\infty}^{+\infty} |E^{(0)}(z)|^2 \, dz}$$

is the fraction of optical power in MQW region (the confinement factor), n_{TE} is given by (6) and

$$\overline{\Delta n} = \frac{\int_{\mathrm{MQW}} \Delta n(z) |E^{(0)}(z)|^2 \, dz}{\int_{\mathrm{MQW}} |E^{(0)}(z)|^2 \, dz} \tag{9}$$

is the average refractive index change in the same region.

For the devices considered in this study, the results of optical simulations reveal that the ratio $\Gamma / n_{\mathrm{eff}}^{(0)}$ varies from 0.1865 to 0.189 for cap layer thicknesses in the range 50–200 nm as we can see from Fig. 8. The ratio $\Gamma / n_{\mathrm{eff}}^{(0)}$ varies linearly with the

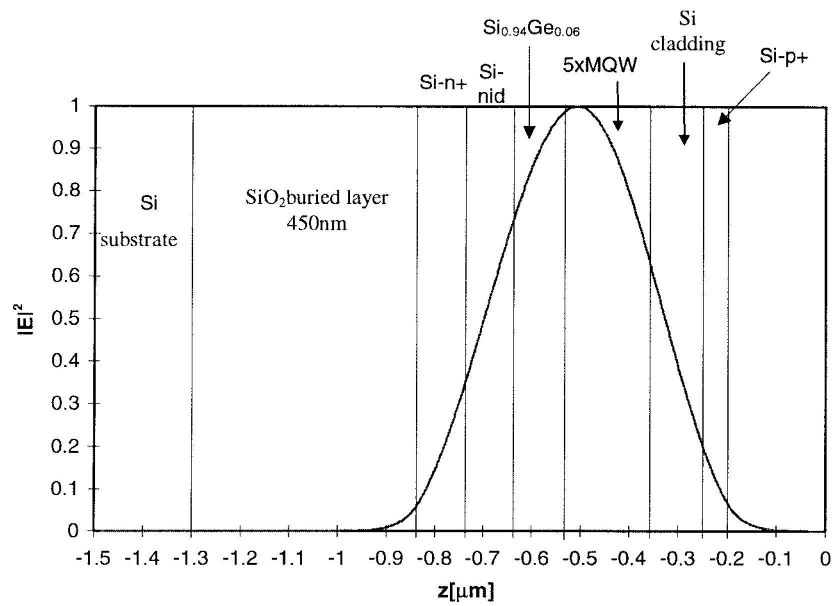


Fig. 7. Field intensity profile in the proposed modulator. The confinement factor in the MQW region is higher than that corresponding to a structure grown on a Si substrate.

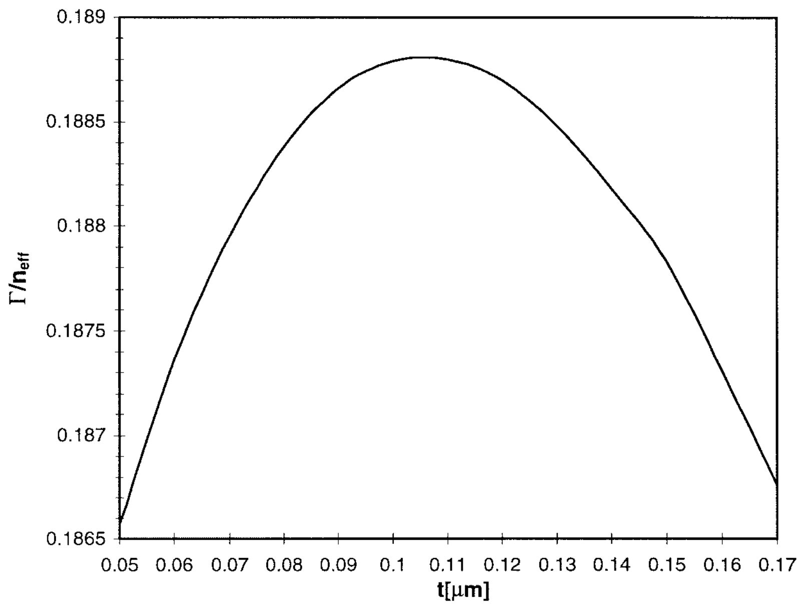


Fig. 8. The variation of the $\Gamma/n_{\rm eff}$ factor as a function of the Si cap layer thickness. This factor varies between 0.1865–0.189 for the cap layer thickness in the range 50–200 nm.

number of QW considered so the effective index change will vary linearly with the number of QW considered.

Finally, we obtain a simplified formula that describes well the effective index change in the entire structure for different cap layer thickness in the range 50–200 nm.

$$\Delta n_{\rm eff} = 0.66 \cdot \overline{\Delta n} \tag{10}$$

where $\overline{\Delta n}$ is given by (9) and describes the average refractive index in the MQW region. To evaluate (9) we used the following Soref and Benett formula for electrorefractive effect in Si [16] as it offers a lower approximation to the effect.

$$\Delta n = -6 \cdot 10^{-18} (\Delta P)^{0.8}. \tag{11}$$

Using the value of $\overline{\Delta n} = 8 \cdot 10^{-4}$ we obtain $\Delta n_{\rm eff} \sim 5.3 \cdot 10^{-4}$, which is a significant effective index change. A phase modulator using this effective index change will have around 1.2 mm length for a π phase shift. Moreover, if we use other type of waveguide interferometers [23] with a resonator finesse between 3–10, we could decrease the length of the device to less than 500 μm.

The waveguide loss due to the free-carrier absorption is given by a formula similar to (7) where $\overline{\Delta n}$ is replaced by an averaged absorption $\overline{\Delta \alpha}$. The waveguide loss is decreasing with about 7.4 dB/cm that corresponds to about 0.9 dB of total insertion loss for a 1.2 mm phase modulator. This value is comparable with the waveguide insertion loss variation in

III–V and Si-based injection modulators due to the variation of the injected free carrier concentration in the waveguide core. An insertion loss variation of $\sim$1 dB for an effective index change of $\Delta n_{\text{eff}} = 5 \cdot 10^{-4}$ was reported in [4] and [5]. However, this is not a problem as the phase modulation is currently used in an integrated optics structure (interferometer) where we could design the high transmission state to correspond to the depleted state so there will be no absorption on free-carriers. A great advantage of the device we described is the possible high speed operation. As it is based on unipolar injection and extraction it is not a device limited by minority carrier recombination times.

The total voltage across the intrinsic region is controlled by the transport of carriers through the device. Once the reverse bias is applied to the diode, two transport processes must take place for the device to achieve the reverse bias steady state. These mechanisms are as follows:

1) escape of the carriers from the wells;
2) drift of the carriers across the depletion layer.

The second process is very rapid (a few tenths of a picosecond) as the distance to the contacts is less then 0.5 μm. The escape process from the QW's is giving the main limitation of this type of charge transfer device. It was found as the main limiting process for other types of charge transfer MQW devices like the barrier, reservoir, and quantum-well electron transfer structure (BRAQWETS) [24] or charge generated MQW modulator like the self-electrooptical device (SEED) [25]. To analyze this process, we used a model developed by Schneider and von Klitzing [26]. They evaluated the time for thermionic emission over the barrier (this is the main carrier escape mechanism from the well) for time-resolved charge-carrier transport perpendicular to the layers of MQW in an electric field.

By applying an electric field across the well, the confined hole concentration will decrease as

$$\Delta P_W(t) = \Delta P_W^{(0)} \exp(-t/\tau_e) \tag{12}$$

where $\Delta P_W^{(0)}$ is the initial confined hole concentration and τ_e is escape characteristic time given by the thermionic and tunneling escape times $1/\tau_e = 1/\tau_{\text{th}} + 1/\tau_{\text{tun}}$.

The thermionic escape time is determined by calculating the probability that a carrier will have sufficient thermal energy to overcome the barrier and can be written as

$$\frac{1}{\tau_{\text{th}}} = \frac{1}{d_W}\left(\frac{k_B T}{2\pi m^*}\right) \exp\left(-\frac{V_i - E_i - qF\,\dfrac{d_W}{2}}{k_B T}\right) \tag{13}$$

where m^* is the hole effective mass, d_W is the well width, V_i is the well barrier height, E_i is the energy eigenvalue, and F is the electric field in the well. The tunneling process could be ignored in the first approximation of the escape time calculation as the voltage required for appreciable tunneling is calculated to be beyond the device breakdown voltage. Moreover, as we could see immediately $\tau_e \leq \tau_{\text{th}}$ so the characteristic escape time has an upper limit from the thermionic characteristic time.

The value obtained for the escape time for a QW with 15-nm width is about 150 ps at 300 K for a zero electric field and decreases to less than 10 ps for a field of 10 V/μm as it was estimated as necessary to fully deplete the well.

Another limitation for the device could be the *RC* characteristic time. We calculated the differential capacitance dQ/dV for our device as being around 1 fF/μm^2. For a 1-mm-long device and 5 μm contact width the characteristic time is less than 250 ps for a 50-Ω load. This analysis shows that in principle the device could operate at frequencies superior to 1 GHz and could allow a possible solution to the Si-based optical modulator speed problem. Further investigation must be done using a more complicated model that takes into account the real refractive index change due to confined hole in a SiGe–Si quantum well. Also, experiments of ultra-fast transverse carrier transport in a strained MQW p-i-n structure using optical pumping could be interesting to understand the carrier transport dynamics and to measure precisely the characteristic times of the processes involved in the functioning of this device.

V. Conclusion

The Si-based injection optical modulators could not operate at frequencies superior to 1 GHz due to limitations associated with recombination of carriers. One strategy for dealing with this problem is to use quantum-confined SiGe–Si heterostructures where the engineering of strain and band gaps leads to new and practical properties not found in bulk semiconductors. We proposed and analyzed theoretically a new type of SiGe–Si modulation-doped multiple-quantum well that allows in principle to achieve operation at a few gigahertz. We presented a model for the calculation of the confined hole concentrations that could be tuned by an external applied electric field. The waveguide structure is proposed to be realized starting with a SOI substrate as this could increase the optical confinement in the MQW active region. A numerical evaluation of the effective index change for our waveguide structure indicates that a value of $5 \cdot 10^{-4}$ could be obtained in practice for a structure with five quantum wells. A phase modulation of π could be obtained for a 1.2-mm-long waveguide. By using an interferometric structure we could decrease the length of an intensity modulator at less than 500 μm. The speed response of the modulator was evaluated using an appropriate model for the escape mechanism from the quantum well as it was demonstrated as being the main intrinsic limitation of the device. The *RC* characteristic of the device is not a limitation for the gigahertz regime functioning of the device. This type of device could be fabricated in a technology fully compatible with the mature Si technology. It could be a building block for a monolithic integration with the existing SiGe–Si HBT microwave circuits that proved already correct functioning at a few tenths of a gigahertz.

Acknowledgment

The authors acknowledge valuable theoretical discussions with A. Koster.

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