Simulation studies of a β-SiC -on-insulator Pockels phase modulator

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ABSTRACT

We have designed waveguide modulators using β-SiC-on-insulator waveguides and the Pockels effect. A 2D semiconductor device simulator was used to determine the electric field configuration in a double-Schottky diode structure. This allowed us to evaluate the local modulation of the refractive index as a function of applied external bias and to determine the effective index modulation of the guided mode. The optical simulations were performed using the Spectral Index and the Effective Index methods. Different 2D geometries are analyzed and the material parameters needed for fabricating such a device are determined. Application to Mach-Zehnder intensity modulators is described. Such devices have potential for high-speed Si-based photonic devices compatible with silicon technology.

Keywords: Si-based optoelectronics, silicon on insulator, active devices, optical modulators and switches, SiC rib waveguides, Pockels effect, high-speed modulators.

1. INTRODUCTION

In recent years Si-based optoelectronics has been intensely investigated with the objective of bridging between the field of optical communication and silicon integrated circuits. In particular, silicon-on-insulator (SOI) based waveguides received significant attention for their potentially low production costs. Since the linear electro-optic effect (Pockels effect) vanishes in crystalline silicon because of the centrosymmetric nature of the crystal structure, devices such as modulators and switches must be designed using the free carrier dispersion effect [1]. Furthermore, the transparent wavelength range of Si is limited to the region of above 1.2 μm, therefore integrated optics applications in the visible range are excluded.

Cubic (3C or β) silicon carbide (SiC) is a wide bandgap (2.2eV) optoelectronic material, transparent over 0.54-2μm and therefore suitable for waveguiding over the visible and near-infrared spectrum range as well as the longer communication wavelengths. SiC polytypes have long been considered as good candidates for high-power and high-temperature devices because of their attractive electronic properties. Cubic SiC is a crystal with a zincblende structure and possesses a $43m$ point-group lattice structure which is non-centrosymmetric. A large electro-optic coefficient, more than 70% higher than that for GaAs, was measured by Tang et al. [2]. Optical devices fabricated from β-SiC can be operated at wavelengths as short as 539nm (the approximate absorption edge at room-temperature) giving much greater scope for additional applications: better resolution for shorter wavelength interferometers, visible signal routing for optical data storage etc. The high mechanical strength and excellent thermal conductivity make it attractive for use at high optical power densities and high-temperatures.

Recently, research groups investigated the optical confinement in SiC planar waveguides but there is no report in the literature of theoretic or experimental investigations of active integrated optics devices. Tang et al. [3] studied experimentally β-SiC waveguides formed by attaching a SiC film to a sapphire substrate. Prucnal and Liu [4] investigated theoretically and proposed some planar SiC waveguides on SiO_2, in structures similar to silicon-on-insulator ones. Recently, Jackson et al [5] reported the first observation of waveguiding in SiC-on insulator [1](SICOI) at 1.52μm. The waveguides were made using a process similar to the SIMOX fabrication method. Further investigations made on these waveguides at 1.3μm have shown reasonable losses (<9dB/cm). More, preliminary results on β-SiC-on-SOI (SICSOI) waveguides made by epitaxial growth of SiC on SIMOX and Unibond substrates [6] indicate that the loss (~8.8dB/cm) could be further reduced by a reduction of the residual doping of the SiC layers($5\cdot10^{17}cm^{-3}$). These waveguides are potentially low-loss.

Based on these experimental results we will present an analysis of phase modulators using SICOI and SICSOI rib waveguides and the Pockels effect. The electric field configuration in double-Schottky diode structures is analyzed in order to calculate and optimize the overlap with the guided mode. Using the results of electrical simulations we have evaluated the effective index modulation of the guided mode using optical field distributions obtained by two well-known methods: the Spectral Index Method(SIM) and the Effective Index Method(EIM). Two different geometries of electrodes are analyzed. They determine vertical or horizontal electric field distribution respectively. Applications to a Mach-Zehnder intensity modulator are described in both cases. The maximum allowed residual doping for the SiC layer is determined for a practical modulator.

2. SIC-ON-INSULATOR LEAKY WAVEGUIDES

2.1 SICOI and SICSOI waveguide structures

There are two practical methods to fabricate SiC-based waveguides.
The first one starts with a β-SiC epilayer grown using CVD methods on a Si substrate [5]. A buried oxide layer could be produced by high-energy(~2MeV) ion implantation of oxygen and subsequent annealing. RBS analysis has shown that while the Si concentration at the O-rich layer is reduced leading to a silicon dioxide (SiO_x ,x=2.04), the carbon is practically all ejected from this layer. The SiO_2/bulk-SiC interface is sharper than the surface-SiC/SiO_2 one. This method is similar to that used for fabricating the SIMOX material.

At the telecommunication wavelengths (1.3 and 1.55 μm) the β-SiC has a refractive index of ~2.57 [7] smaller than that of Si (~3.5). For waveguiding purposes the upper and lower cladding regions must have a lower refractive index. The silicon dioxide has a refractive index of 1.45. Nevertheless the air(cover)/SiC/SiO_2/SiC/Si(substrate) structure form a waveguide, but the presence of a high refractive index Si substrate potentially transforms it into a leaky waveguide. The degree of loss is determined by the buried oxide thickness as the light propagating in such a waveguide could escape into the substrate by an effect analogous to the tunnel effect in quantum mechanics. The thickness of both the SiC guiding film and buried oxide layer could be adjusted by choosing different implant energies and doses. Starting with a 2μm SiC layer on a silicon substrate, for the 2MeV implant we expect a waveguide with about 1.2μm of SiC, separated by 0.2μm of buried oxide from a remaining 0.6 μm SiC layer and the Si substrate. The cross section of this SiC-on-insulator(SICOI) waveguide is depicted in figure 1a. As the thickness of the SiC waveguide core could not exceed 1.2μm a lateral electrode configuration is necessary to form a modulator in this type of waveguide. The theoretical propagation loss due to leakage to the substrate for TE/TM polarisations at 1.3μm is reported in figure 2. For a buried oxide greater than 0.3μm the loss is less than 1dB/cm for the two polarisations.

The second method to fabricate SiC waveguides gives us much more flexibility for the range of thicknesses of the SiC waveguide core and for the buried oxide. It is based on epitaxial growth of β-SiC on SOI substrates (SIMOX, Unibond). The good quality of such epitaxiated films has already been demonstrated in the fabrication of high-breakdown 6H and 3C-SiC diodes with a better isolation from the substrate than the SiC/Si ones. There are problems related to the residual doping of such epitaxial layers but the new developed site-competition epitaxy [8] offers the possibility to obtain semi-insulating layers that are necessary for the fabrication of a Pockels modulator. The actual range of residual doping that is achieved is $5\cdot10^{15}$-$10^{16}cm^{-3}$ with the potential to obtain in some cases less than $5\cdot10^{14}cm^{-3}$.

Such air(cover)/SiC/Si/SiO2/Si(substrate)structures (see figure 1b))are low-loss optical waveguides for buried oxide layers thicker than 0.4μm. Despite the higher refractive index of the Si, the waveguide mode propagates mostly in the thicker SiC layer(see figure 5). The propagation loss for TE/TM polarisations at 1.3μm are less than 0.5dB/cm for a a structure SiC (2μm)/Si(0.2μm)/SiO_2(0.4μm).

Experimental investigation of of SICOI and SiCSOI waveguides have shown reasonable extra-losses due to the surface and volume scattering and to the absorption on the residual free carriers. Further improvement in the fabrication of the SiC epi-layers will allow a reduction of the waveguide loss to less than 5dB/cm which is reasonable for a Pockels modulator having less than 3mm length [6]. As a comparison modulators using the electro-optic effect in GaAs are currently reported with waveguide insertion loss in the range from 1 to 2dB [9].

3. β-SIC WAVEGUIDE MACH-ZEHNDER MODULATORS

3.1 Vertical geometry.

A schematic drawing of a Mach Zehnder modulator is shown in figure 3. As both the SICOI and SiCSOI substrates have a (100) orientation the electric field could be applied only in <100> and <011> directions. The first case corresponds to a vertical geometry with an electrode on top of the rib waveguide. The second one corresponds to a lateral positioning of the electrodes in order to achieve a horizontal electric field.

For the vertical geometry (figure 4) the field E_y induces a local electrooptic index change for the TE polarized optical field propagating in the z direction given by:

$$\Delta n = \frac{n^3}{2} r E_y \qquad (1)$$

Where n is the refractive index (n_{SiC}=2.57), $r=2.7\cdot 10^{-10}$cm/V ^{2} is the Pockels coefficient and E_y the applied vertical field.

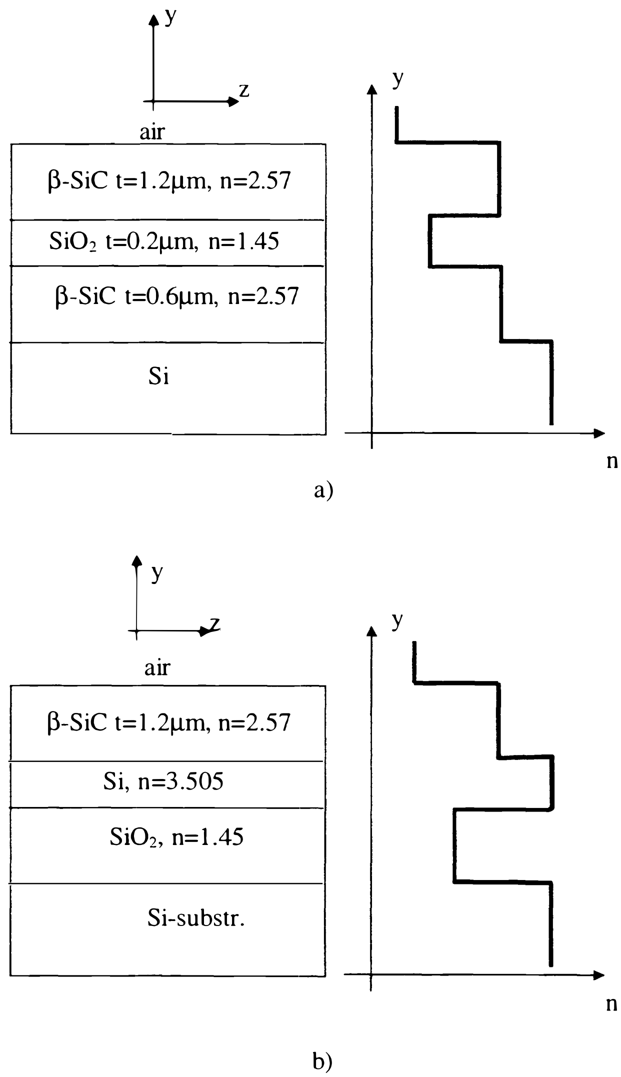

Fig. 1 a) SiCOI waveguide structure made by high-energy ion implantation of oxygen in SiC(2μm)/Si substrates. b) SiCSOI waveguide structure made by epitaxial growth of SiC on SOI substrates.

The effective index change due to the applied field within a cross section of the optical mode can be written as:

$$\overline{\Delta n(V)} = \frac{n^3 r}{2} \cdot \frac{V}{d} \Gamma \tag{2}$$

where V is the applied voltage, d the inter-electrode gap and Γ is the overlap integral between the applied electric field and the optical mode. Γ is given by:

$$\Gamma = \frac{d}{V} \frac{\iint E_y(x,y) \cdot |E(x,y)|^2 dxdy}{\iint |E(x,y)|^2 dxdy} \tag{3}$$

with $|E(x,y)|^2$ being the optical field distribution propagating in the z direction, and $E_y(x,y)$ the applied electric field.

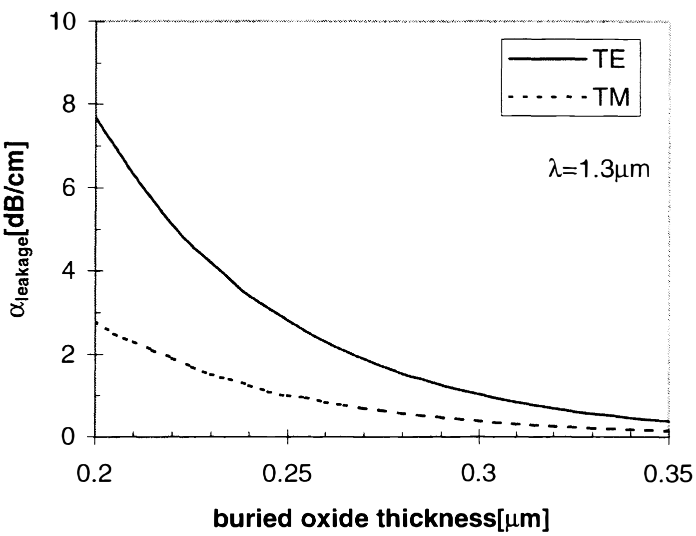

Fig.2 Propagation loss in a SiCOI waveguide by leakage toward the substrate as a function of the buried oxide thickness.

The total phase shift over the interaction length L is then:

$$\Delta\beta\,\mathrm{L} = \frac{\mathrm{n}^3 r}{2} \Gamma \cdot \frac{V}{d} \cdot \frac{2\pi \mathrm{L}}{\lambda} \tag{4}$$

Intensity modulation could be achieved in the Mach-Zehnder waveguide interferometer and nominally complete extinction could be obtained for $\Delta\beta\,\mathrm{L} = \pi$ which give us an important parameter of the modulator, the half-wave voltage:

$$V_\pi = \frac{\lambda d}{n^3 r \Gamma \mathrm{L}} \tag{5}$$

For a given electrooptic material one tries to minimize $V_\pi \cdot L$ by optimizing the geometrical parameter d/Γ.

The two dimensional distribution of the electric field was modeled using a device simulator (SILVACO [10]) and the overlap integral was calculated using the optical field distribution obtained by Spectral Index Method [11]. This method is very precise as demonstrated by several authors offering a precision of better than 10^{-5} for the value of guided mode. It has the advantage of producing a separable solution for the optical field. The simple Effective Index Method(EIM) was also tested. Currently, we obtain a negligible difference (less than 0.1%) for the overlap integral using the field generated by this method. For design purposes when the structure parameters must be slightly modified we used this method as it is very simple and rapid to implement.

As an example figure 5 shows the fundamental mode intensity distribution for the structure shown in figure 4 calculated using the Spectral Index Method.
A question may arise regarding the loading loss due to the metallic electrodes. Using the EIM we estimated the loading loss due to gold Schottky contacts as less than 0.9dB/cm for central waveguide heights $H \geq 2.5\mu m$.

Figure 6 shows a 2D contour plot of the applied electric field together with the distribution along a cross-section in the central region of the structure, for an applied anode bias of V_{anode}=-50V and a residual n-doping of $10^{15}cm^{-3}$. It can be seen that the SiC layer is fully depleted and the averaged refractive index modification is $\overline{\Delta n} = 2.71 \cdot 10^{-4}$. The length of the modulator to achieve a π phase shift must be L_{π}=2.4mm. A $V_{\pi}L_{\pi}$=120Vmm is predicted for this structure.

For a residual n-doping of $10^{16}cm^{-3}$ the field touches the Si region for V_{anode}=-50V and the corresponding averaged effective index modification is $\overline{\Delta n} = -2.45 \cdot 10^{-4}$ (L_{π}=2.65mm). In the case of a residual n-doping of $10^{17}cm^{-3}$, $\overline{\Delta n} = 1.46 \cdot 10^{-4}$. In this case the depletion region extends just in a region of about 1.1μm under the anode. There is also an important effect of free carriers, as depletion of electrons causes the refractive index to increase. Using the simplified Drude Lorenz formula we calculated an averaged effective index modification of $\overline{\Delta n_c} = 9.63 \cdot 10^{-5}$. This acts as a parasitic effect for this case where the SiC layer has a relatively high residual doping.

Therefore for a feasible modulator a residual doping lower than $10^{16}cm^{-3}$ will be preferable as the depletion of the SiC layer could be achieved efficiently and with no parasitic free-carrier effect.
We observed a reduced dependence on the distance between the anode and the two lateral electrodes in the range 3 to 5μm, as the important vertical field is concentrated mainly in the central region. The lateral electric field is at least 2 orders of magnitude less than vertical field.

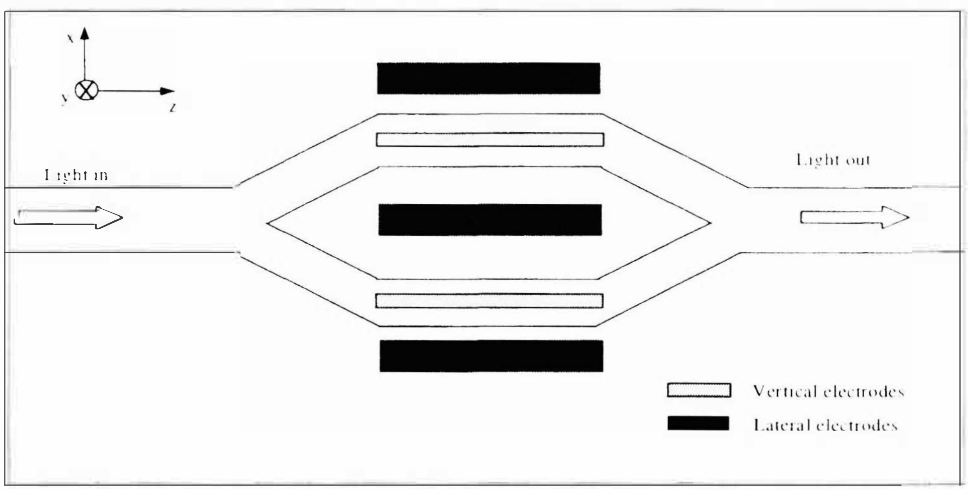

Figure 3. Schematic view of a Mach-Zehnder waveguide modulator using vertical or horizontal geometry. For the vertical geometry the bias is applied between the top Schottky electrode and the lateral ones. For the horizontal geometry there are no top electrodes and the bias is applied between lateral electrodes.

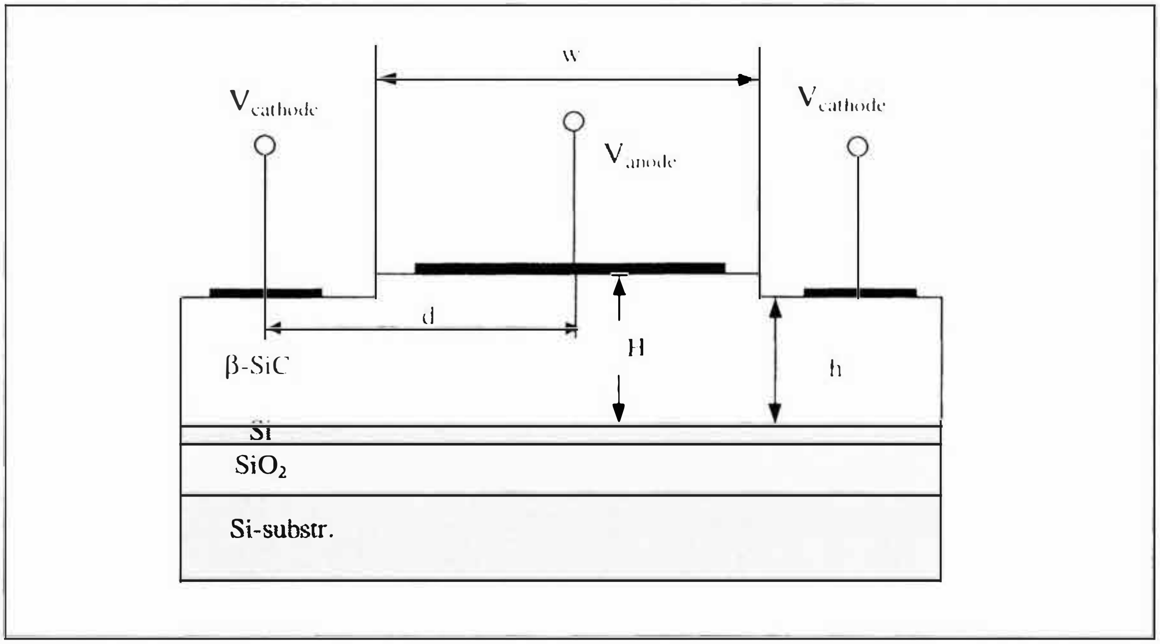

Figure 4 Schematic view of a SiCSOI rib waveguide phase modulator. The SOI substrate is considered a standard one t_{Si}=0.2μm, t_{SiO_2}=0.4μm. The width of the rib is w=3μm. The two lateral electrodes(cathodes) are considered 1μm wide and the anode is considered 2μm wide. The other dimensions are:H=2.5μm, h=2.0μm. The waveguide is single-mode for rib widths less than 3.5μm.

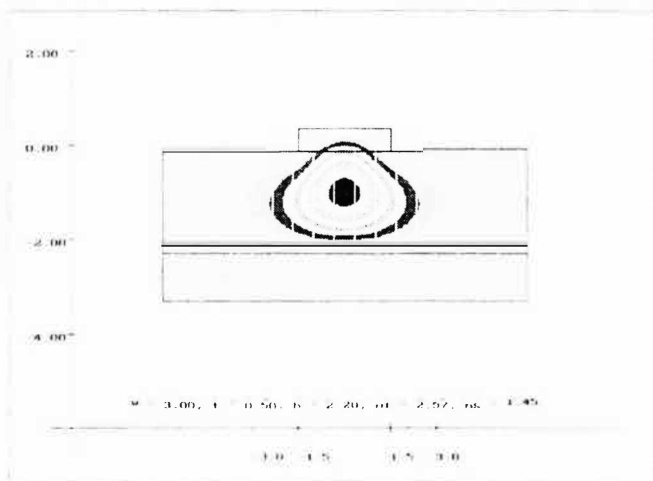

Figure 5. The fundamental mode normalized intensity distribution calculated with the Spectral Index Method for the structure shown in figure 4. The contour plots are traced for a 0.1 step except the last one corresponding to 0.01. The dimensions are in microns in both vertical and horizontal directions. The thickness h in the lateral region is the sum of the SiC(2μm) and Si layer(0.2μm) layer thicknesses

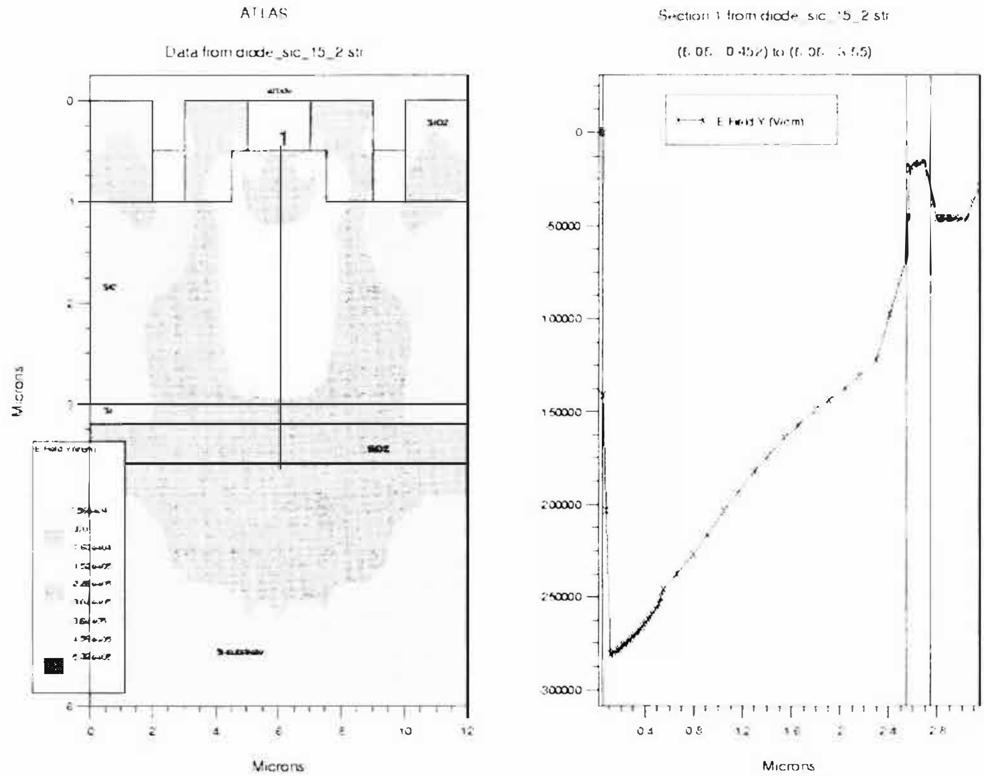

Figure 6. Electric field distribution in the SICSOI diode (vertical field) for a V_{anode}=-50V and a distance anode-cathodes of 3.5μm (calculated between the centers of the electrodes). The second plot shows a section in the central region of the structure. The SiC layer is fully depleted and a significant vertical field is established in the rib region.

3.2 Horizontal geometry

The horizontal geometry of electrodes [12] could also be used in a Mach-Zehnder modulator(see figure 7). The index ellipsoid is perturbed through the electrooptic effect in the plane perpendicular to the propagation direction (< 011 >).

The major and minor axes of the resultant index ellipsoid are at 45° with respect to the main TE and TM eigenmodes of the waveguide as illustrated in figure 7. The index increase Δn along the major axis is equal to the index decrease along minor axis and is given by

$$|\Delta n| = \frac{n^3}{2} r |E| \quad (6)$$

where E is the applied electric field, r is the Pockels coefficient and n is the index of refraction.

This index ellipsoid acts to couple the TE and TM eigenmodes of the unperturbed waveguide.
It can be shown that the induced birefringence will modify the TE, TM propagation constants by an equal amount Δβ given by:

$$\Delta\beta = \delta - \sqrt{\delta^2 + \kappa^2} \quad (7)$$

where $\delta = (\beta_{TE} - \beta_{TM})/2$ is the detuning parameter and $\kappa = 2\pi/\lambda \cdot \Delta n = 3.52 \cdot 10^{-5} E[V/cm]$ is the coupling constant expressed in rad/cm.

Also, a transfer of energy occurs between TE and TM eigenmodes. This is governed by the following expression for the normalized amplitude of one of the eigenmodes:

$$A(z) = -ie^{i\delta z}\frac{\kappa}{\left(\kappa^2+\delta^2\right)^{1/2}}\sin\left[\left(\kappa^2+\delta^2\right)^{1/2}z\right] \quad (8)$$

As the A(z) depends on the sign of κ, the modes at the output could be made of opposite phase if the electric fields in the two arms of the Mach-Zehnder have opposite directions. When combined in the single-mode output section of the Mach-Zehnder we obtain total extinction. The modulator functions exactly like the previous Mach-Zehnder except that the higher order radiation mode that radiates in the single-mode section has complementary polarization. For $0 \leq \left(\kappa^2+\delta^2\right)^{1/2} L \leq \pi/2$ we obtain different degrees of modulation and the polarization at the output will be the same as the polarization of the input.

The normalized power of one of the eigenmodes $|A(z)|^2$ is shown in figure 8 for different δ and κ for a Z=4mm modulator.
For the SICOI rib waveguide the δ parameter has a large value (δ=77) which determines very low coupling between TE and TM. A transfer of just 15% of the energy is obtained for a κ=30 rad/cm which is attained for an averaged electric field of about 10^6V/cm. The waveguide with δ=9 corresponds to the SiCSOI rib waveguide in figure 4. In that case applying a voltage bias between the two cathodes, a κ=8rad/cm is necessary to transfer near 45% of the power between the eigenmodes. This could be achieved for a reasonable electric field situated around $2.5\cdot10^5$V/cm which is much easier to obtain in practice. One of the advantages of using SiC is the high breakdown field. As a matter a fact the value $2.5\cdot10^5$V/cm is close to the breakdown of both Si and GaAs but 10 times less than the breakdown field achievable in SiC($2\cdot10^6$V/cm).
For the SICOI rib waveguide the vertical geometry is not feasible due to the high metal load loss (>12dB/cm for TE and >180dB/cm for TM). We conclude that a SICOI rib structure with practical dimension that could be achieved by ion implantation of oxygen is not a good one unless a high electric field is applied, close to the breakdown field of the SiC($2\cdot10^6$V/cm). Furthermore, the modulation depth expected for such a device is low (less than 15%).

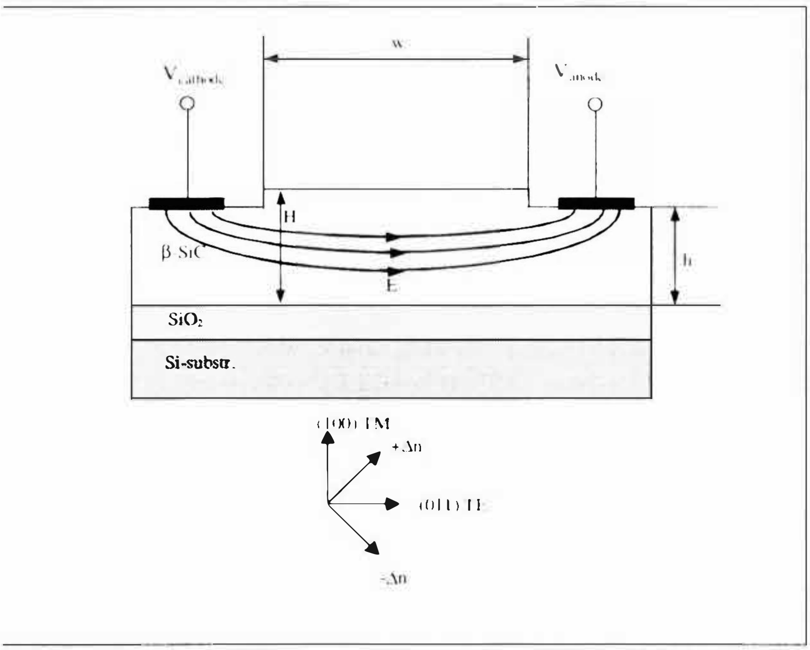

Figure 7. Cross-sectional view of a SICOI rib waveguide modulator with a lateral geometry of electrodes. The electric field is oriented in the <011> direction and the major and minor axes of the index ellipsoid are also indicated. The dimensions are w=3μm, H=1.2μm and h=1μm.

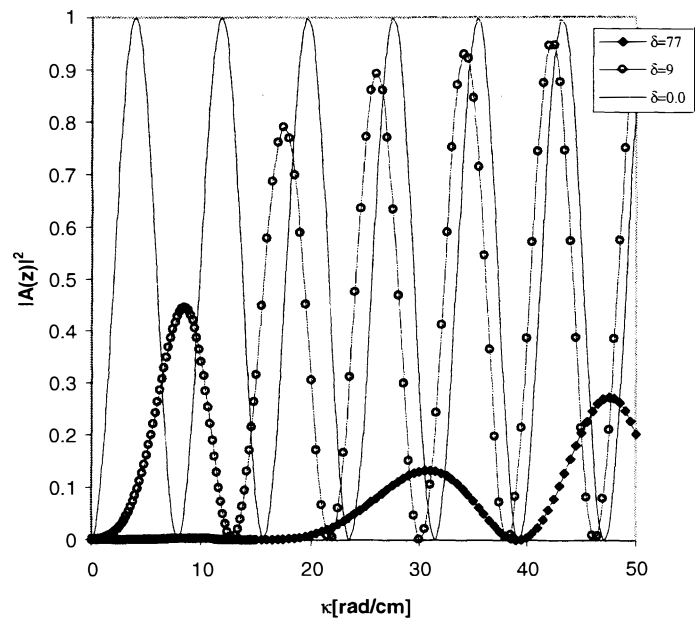

Figure 8. Eigenmode power conversion factor for a 4mm long modulator as a function of coupling constant with the detunig factor between TE and TM modes δ as a parameter. The case δ=9 rad/cm corresponds to the waveguide shown in figure 5 and the case δ=77rad/cm to the waveguide shown in figure 8.

4. CONCLUSIONS

We have analyzed two practical configurations of SICOI and SICSOI phase modulators using the Pockels effect in β-SiC. The conclusions of this study are that waveguides made using ion implanted SiC/Si are suitable for phase modulation in the case where an extremely high electric field is applied (close to the breakdown field of SiC). The performance is rather poor as a modulation depth of 15% is predicted. This is mainly due to the highly detuning parameter of the rib waveguides made using thin SiC layers. Furthermore, increase in the thickness of the guiding SiC is difficult as high energy ion implantation was considered (2MeV), and higher energy is difficult to obtain for most implanters.

The structures of SICSOI waveguides made by epitaxial growth of SiC on SOI substrates looks more promising for both vertical and lateral configurations of electrodes. However, good quality epitaxial growth, as well as a relatively low level of residual doping of the SiC layer($<10^{16}cm^{-3}$) are required. The modulator could function in this case at applied voltages not exceeding 50V for electric fields 10 times less than the breakdown voltage of the SiC material. The corresponding (half-wave voltage)·(length) product for the modulator is ~120V·mm.

The main interest in SiC based modulators resides in the compatibility with the mature silicon technology together with the possibility to fabricate very high-speed integrated optics devices or photonic devices operating in high temperature/high corrosion environments.

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