Design, Fabrication and Characterization of an α - Si:H / α - SiCN waveguide multistack for electro-optical modulation

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ABSTRACT

This paper reports the design, fabrication and characterization of a planar waveguide based on an hydrogenated amorphous silicon (*a*-Si:H) – silicon carbonitride (SiC_xN_y) multistack for the realization of passive and active optical components at the wavelength 1.3 - 1.5 µm. The waveguide was realized by low temperature plasma enhanced chemical vapour deposition (PECVD) compatible with standard microelectronic technologies. Electro-optical modulation at λ= 1.5 µm is demonstrated in this waveguide. The device operates by varying the free carrier concentration to change the Si absorption coefficient in the guiding region. It has been modelled using the two-dimensional (2-D) device simulation package SILVACO and the optical simulator Beam PROP to determine its electrical and optical performances, respectively.

Keywords

Integrated optics, modulator, electrooptics, electroabsorption, waveguides.

1. INTRODUCTION

Optical switches and modulators are essential components for some integrated optic applications. Thanks to its cheap and well established technology crystalline silicon (c-Si) is an ideal candidate for the realization of these optoelectronic devices in the near infrared region, an ample volume of work exists in the field [1, 2].

For decades, hydrogenated amorphous silicon (*a*-Si:H) was considered as an optoelectronic material almost exclusively for low-cost photovoltaic applications. Only recently new applications have been proposed in the optical communication area for the detection of photons [3], and for lightwave guiding [4]. All-optical and thermo-optical effects have also been exploited in *a*-Si:H to demonstrate modulation or switching actions in planar devices for integrated photonic [5, 4]. Electro-optical effects have been rarely considered in this material due to the weak incidence of electric field on the refractive index [6], on one side, and the difficulty of reaching effective carrier injection across p-n junctions in amorphous semiconductors.

In this paper, we report results on light modulation through field-induced carrier accumulation in a 1.2-cm-long *a*-Si:H/*a*-SiCN multi-stack waveguiding structure deposited by low-temperature PECVD on a c-Si substrate. The Si_3N_4 cladding layer and the good quality of the *a*-Si:H confer the waveguide strong vertical confinement and low losses at λ = 1.5µm.

2. DESIGN AND FABRICATION

The cross section of the realized device is sketched in Fig. 1. It consists of three alternate bi-layers of 1 µm-thick *a*-Si:H with 30 nm *a*-SiCN, deposited on a <100> Silicon substrate. The substrate and the stack are separated by a 0.39 µm-thick Si_3N_4 low refractive index cladding layer. Due to the steep change in the refractive indices between the two materials (*a*-Si:H and Si_3N_4), Δn ≈ 2, a strong vertical confinement is achieved. A transparent conductive ITO thin film forms the top contact, while the bottom contact is the Si substrate itself.

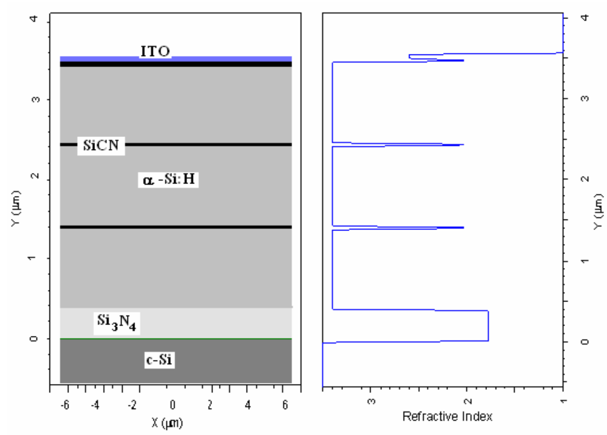

Figure 1. Schematic cross section of the realised planar waveguide (left) and the corresponding refractive index depth profile (right). The crystalline silicon substrate is 300 µm thick.

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In earlier works [7] the ternary (Si, N, C) was exploited aiming at the production of a material with good insulating electrical properties and improved interfaces with amorphous silicon.

Optimized samples of SiC_XN_Y are, to date, applied only as dielectric layer to *a*-Si:H thin film transistors (TFTs) in place of the traditional SiN_X gate insulator.

In our device the three thin *a*-SiCN highly insulating layers break the conduction between the *a*-Si:H films so that the device electrically behaves in fact as the series of three capacitors. The application of a voltage across the stack therefore produces an accumulation of electrons and holes respectively at the opposite sides of the dielectric films, and therefore at intermediate depths across the waveguide. This approach has been proven to enhance the free carrier induced effects on the optical propagation characteristics. The carrier distributions under bias were first determined in the structure by performing electrical simulations with *ATLAS.* A similar device, but designed for crystalline silicon technology, was recently proposed by Barrios [8].

The fabrication begins with a surface-smoothing treatment, using H_2SO_4+H_2O_2 and HF solutions on the n-type highly doped c-Si substrate (ρ=0.025 Ω-cm). The substrate is then loaded into the four-chamber RF (13.56 MHz) system. First, a 0.39 μm layer of Si_3N_4 is deposited from the plasma-assisted decomposition of SiH_4 and NH_3, at a RF power of P_{RF} = 4W. Subsequently, a 1 μm thick *a*-Si:H layer is deposited in SiH_4 atmosphere, followed by the deposition of the *a*-SiCN from a gaseous mixture of SiH_4, NH_3 and CH_4. Forth / fifth and sixth / seventh depositions were made under the same conditions as the second / third ones. Temperature was 220°C for all steps and the total deposition time was approximately six hours. The top ITO film was deposited by magnetron sputtering and is 80 nm thick.

Table 1 summarizes the fundamental process parameters. The refractive indices *n* of the films were measured on separate samples deposited on corning glass under the same conditions. Data at λ= 1.55 μm are also reported in Table 1.

3. NUMERICAL SIMULATION RESULTS

As mentioned, from an electrical point of view, the proposed structure, made of alternate layers of a-Si:H and *a*-SiCN, in fact behaves as a series of capacitors. The application of a biasing voltage between the ITO layer and the substrate determines an accumulation of holes and electrons at the opposite sides of each internal *a*-SiCN insulating layer.

The carrier distributions under bias were first determined in the structure by performing electrical simulations with a finite element CAD code specifically designed for the simulation of solid-state devices including amorphous semiconductor regions, *ATLAS* [10]. The fig. 2 illustrates the excess electrons and holes across one *a*-Si:H layer, between the two interfaces with *a*-SiCN, for applied biases of 3V and 20V across one *a*-SiCN/a-Si:H/*a*-SiCN stack.

The waveguide propagation losses were measured by the cut-back technique. We calculated a loss coefficient of 1.1 ± 0.2 dB/cm.

This value is in agreement with that estimated by the numerical electromagnetic-wave solver based on the Beam Propagation Method (BPM) [11]. The resulting attenuations for the TE_0 and TM_0 modes were, in fact, 1.2 and 2.0 dB/cm, respectively.

According to numerical simulations, a single mode waveguide is obtained starting from the proposed structure once a 15 μm wide rib is defined by wet etching in HCl solution of the ITO top layer.

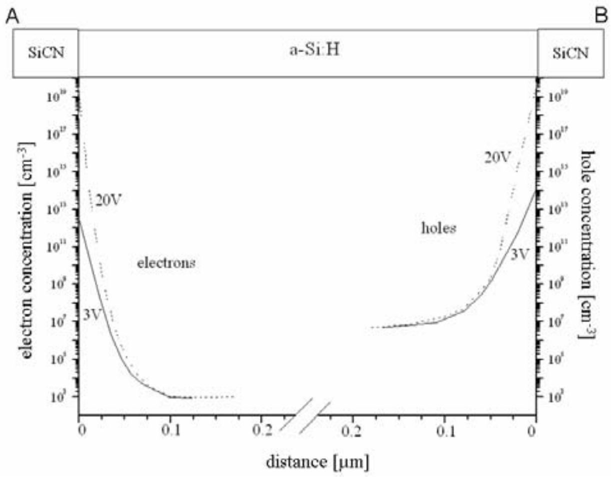

Figure 2. Electron and hole concentration profiles calculated close to the a-Si:H/SiCN interfaces. The applied biases are 3V and 20 V, measured between A and B in the same figure.

4. ELECTRO-OPTICAL MODULATION

In this section the optical and modulation characteristics of the device are presented and discussed.

The principle used to modulate the light signal is the variation of the free carrier concentration at the multiple *a*-Si:H/*a*-SiCN interfaces. The Si refractive index and absorption coefficient depend on free carrier concentration by the dispersion relation [9] that can be derived, in first order approximation, from the classical Drude model:

$$\Delta n = -\frac{e^2\lambda^2}{8\pi^2 c^2 \varepsilon_0 n}\left(\frac{\Delta N_e}{m_e} + \frac{\Delta N_h}{m_h}\right) \quad (1)$$

$$\Delta \alpha = \frac{e^3\lambda^2}{4\pi^2 c^3 \varepsilon_0 n}\left(\frac{\Delta N_e}{{m_e}^2 \mu_e} + \frac{\Delta N_h}{{m_h}^2 \mu_h}\right) \quad (2)$$

Table 1. Deposition parameters, conductibility σ, refractive index *n*, and absorption coefficient α measured at 1.5 μm

Material	RF (MHz)	P gen (W)	Pres (mbar)	T sub (°C)	t dep (min)	Process Gas (sccm)	n	α (dB/cm)	σ (S/cm)
Si_3N_4	13.56	4	0.8	220	26'	SiH_4 1.5, NH_3 68	1.774	-	-
a-Si:H	13.56	4	0.53	220	1^h48'20''	SiH_4 20	3.4	1.027	2.6 10^{-9}
a-SiCN	13.56	4	0.53	220	3'5''	SiH_4 8, NH_3 24, CH_4 8	2.03	-	5.2 10^{-16}

where Δn and $\Delta\alpha$ are the variations of the real part of the refractive index (n) and of the absorption coefficient (α) due to the free carrier concentration change, e is the electron charge, ε is the permittivity in free space, n is the refractive index of intrinsic Si, μ is the free carrier mobility, m are the effective masses, ΔN is the free carrier concentration variation, and λ is the wavelength. The subscripts e and h refer to electrons and holes, respectively.

As mentioned, the multilayer stack we presented consists of *a*-SiCN films (order of tenths of nanometres) with a measured conductivity around $\sigma = 5.2 \times 10^{-16}$S cm^{-1} which is seven orders of magnitude lower than amorphous silicon.

The presence of the 30 nm *a*-SiCN between two layers of *a*-Si:H creates a capacitive device. By applying an external electric field, a carrier accumulation is created at the *a*-Si:H/*a*-SiCN interfaces. The effect of introducing three *a*-SiCN regions enhances the overall number of accumulated free carriers distributed across the waveguide cross section, and consequently, increases the modulation efficiency with respect to conventional waveguide modulators based on the variation of the absorption coefficient.

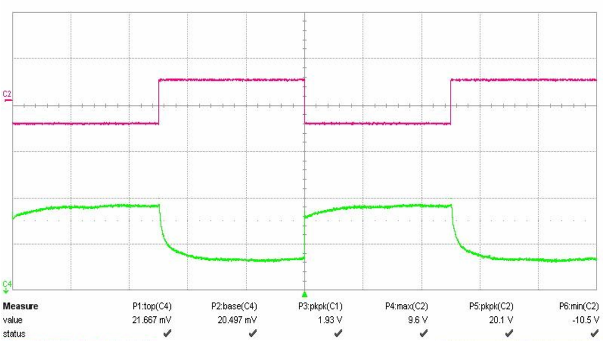

Figure 3. Transmitted modulated intensity light and square voltage pulses applied to the electrodes.

Figure 3 shows the modulated light intensity at the output and the signal voltage applied across the device. When an electric field is applied, according to the Drude theory, the free carrier population induced in the semiconductor (*a*-Si:H) results in a change of the infrared dielectric properties, in particular increasing the absorption coefficient. In this condition the modulator is held in the on-state. The most direct parameter that can be measured is the modulation depth, defined as:

$$M = \frac{I_{MAX} - I_{MIN}}{I_{MAX}} \qquad (3)$$

where I_{MAX} and I_{MIN} are the maximum and minimum intensity of the transmitted signal. By applying a square waveform $V_{peak\text{-}peak}$= 20V a modulation depth of ~7% is obtained.

Moreover, the dependence of M on the amplitude of the modulating signal is shown in Fig. 4.

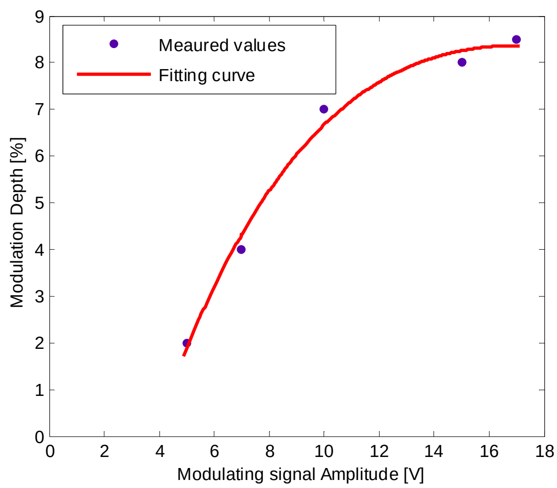

Figure 4. Dependence of *M%* on the amplitude of the modulating signal.

As expected, increasing the $V_{peak\text{-}peak}$ applied across the device, which leads to higher carrier accumulation at the Si:H/*a*-SiCN interfaces, a rise of M is obtained around 9%, where the phenomenon saturates.

5. CONCLUSION

In the present paper we described a new planar based waveguide consisting of an *a*-Si:H/*a*-SiCN waveguide multistack deposited by low-temperature PECVD on a c-Si substrate. Propagation losses as low as 1.2 dB/cm have been measured at λ =1.55 μm.

The presence of three *a*-SiCN regions interposed between *a*-Si:H layers results to be very positive in order to induce a higher carrier accumulation and, consequently, to increase the modulation efficiency with respect to conventional waveguide modulators based on the variation of the absorption coefficient.

The modulation depth *M* was measured in correspondence of square voltage pulses applied; *M* data are observed to increase with the amplitude of the modulating signal.

Technologically, the fabrication process, involves temperatures under 220°C, being this fully compatible with standard microelectronic processes and in particular suitable to realization of optoelectronic integrated circuits.

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