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Optimization of the contact resistance in the interface structure of n-type Al/a-SiC:H by thermal annealing for optoelectronics applications

Roberto Ambrosio*[,1], Alfonso Torres[2], Carlos Zuñiga[2], Mario Moreno[2], and Jose Mireles Jr.[1]

[1] Technology and Engineering Institute, Ciudad Juarez University UACJ, Av. Del Charro 450N, 32310, Chihuahua, Mexico
[2] National Institute for Astrophysics Optics and Electronics INAOE, Luis E. Erro 1, PO Box 51 & 216, 7200, Puebla, Mexico

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* Corresponding author: e-mail rambrosi@uacj.mx, Phone: +52 656 688 4841ext 4571, Fax: +52 656 688 4841

The presented work meets the requirements for integration of amorphous silicon carbon films with silicon technology in order to obtain a complete optoelectronic system such as light emitting diodes and its electronic readout circuits. The key enabler for this integration scheme is the low temperature of deposition of a-SiC:H films and an ohmic behavior in the interface metal/a-SiC:H. In this work, the optimization of the interface Al/a-SiC:H films are performed by means of thermal annealing timing. The a-SiC:H films were deposited by enhanced chemical vapor deposition from CH_4/SiH_4 and C_2H_2/SiH_4 mixtures. The structural and optical properties of the deposited films are presented. An implantation phosphorous dose was used for doping before fabrication of patterned aluminum contacts. The implanted films were electrically characterized by the transfer length method (TLM) measuring a sheet resistance value as low as 171 MΩ/square. The Schottky behavior was improved to ohmic behavior after several hours in thermal annealing treatments at 350 °C, which allows to obtain a reasonable contact resistance values in the range from 8.6 to 26.8 kΩ.

1 Introduction Hydrogenated amorphous silicon carbide (a-SiC:H) thin films have been extensively studied due to their excellent thermal and optical properties, which make them suitable for several applications in the field of microsystems and mainly in optoelectronics. Taking the advantage of adjusting the carbon content these films have been used for development of thin-film light-emitting diode (TEFLED) [1], solar cells [2], thin-film transistors (TFT) [3], and structural layers and masks for silicon micromachining [4].

a-SiC:H films have been developed using different techniques of deposition: plasma-enhanced chemical vapor deposition (PECVD) [1, 12, 13], electron cyclotron resonance CVD [5], and sputtering [6, 9, 10] among others. Currently, PECVD is the most used technique to deposit SiC:H films due to the following reasons: control of deposition [1], development compatibility with large-area electronics devices, and the low-temperature deposition process that makes this technique compatible for integration with optoelectronics and MEMS devices with silicon technology. In most of the investigations the a-SiC:H films are obtained from the mixture of silane (SiH_4) or disilane (SiH_6) and CH_4,C_2H_2,C_2H_4, etc.

For applications of a-SiC:H films for development of solar cells, the films must have high conductivity and low defect density, which can be obtained by means of doping with either boron or phosphorous [7], in gas phase. The properties of a-SiC:H films doped using different gases (B_2H_6 and PH_3) have been extensively investigated [7, 8]. Ion implantation techniques for doping offer the advantage of a better control of impurity concentration. Nevertheless, the ion implantation creates damage in the network and voids due to ion bombardment, which results in an increase on the density of localized states [7]. It is well known that the method to recover the damage is to perform an annealing process at high temperatures.

However, the quality of the films can be optimized by means of tailoring the properties of the films or changing the method of deposition. Few works have been carried out to promote a good ohmic contact in the interface metal/a-SiC:H to improve the performance of the devices [9, 10], allowing the use of simpler methods for process integration to extend

the applications of the a-SiC:H films for complete optoelectronics system development into crystalline silicon (c-Si). For example, in Si-based light emitters, the films can be deposited at a very low temperature and integrated with readout electronic circuits on Si. But the optimization of the ohmic contacts is one of the major concerns in the fabrication of LEDs, the poor electrical properties in the contact interface cause the device to have a lower thermal stability and reliability. In this way, few works have reported the optimization of Al/a-SiC:H interface [9]. In Ref. [9] Al/a-SiC:H Schottky diodes were optimized by thermal annealing and the electrical properties of the diodes are improved at 600 °C. However, there is not enough available data using thermal annealing to switch from Schottky to ohmic behavior. Therefore, we addressed the problem for obtaining good ohmic contacts. The work presents an experimental study of the optimization of the contact resistance for the interface Al/a-SiC:H by means of thermal annealing and ion implantation. The implanted films were electrically characterized by the transfer length method (TLM) for sheet and contact resistance measurements.

2 Experimental

2.1 a-SiC:H films by PECVD The samples of amorphous silicon carbide films were deposited by LF PECVD using an AMP 3300 PECVD system from Applied Materials. SiH_4, C_2H_2, and CH_4 were adopted as the gas sources without hydrogen dilution and one sample with CH_4 for comparison of the optical bandgap. Also, two different substrates were used, Corning 1737 glass for optoelectronics properties and c-Si for measurements of infrared spectra. The films were deposited at substrate temperature $T_d = 350$ °C. The parameters of deposition were as follows: Pressure $P = 0.6$ Torr, RF power $W = 200$ W, frequency $f = 110$ kHz, and time $t = 40$ min. The parameters of deposition are listed in Table 1. The carbon gas phase composition x, defined as the gas flow ratio of $x = [C_2H_2]/[SiH_4] + [C_2H_2]$, and the acetylene content were $x = 0.75$ and 0.96.

The thickness of the films was measured by alpha step equipment model 200 "Tencor Instruments." The IR absorption spectra of the films were measured by the "Bruker"-IR infrared Fourier spectrometer model V22. The range of wave numbers was from 350 to 4000 cm^{-1}.

2.2 Doping of a-SiC:H by ion implantation and fabrication of test structures The a-SiC:H films used in this experiment were deposited on n-type Si (100) substrates and a 0.5-μm thick SiO_2 layer was grown by wet oxidation. Before the films were implanted with phosphorous doses, a thin metallic layer of aluminum was deposited by e-beam evaporation; this metal was used as a masking layer with a thickness of 20 nm to obtain the maximum peak of concentration at the projected range of 20 keV. Prior to performing the doping process, SRIM–TRIM software was used to simulate the impurities distribution ion profile. The samples were implanted, with a dose of phosphorous, to produce concentration of 1×10^{16} cm^{-3} and the energy of implantation of 130 keV. A test structure was fabricated in order to extract the sheet and contact resistance using the TLM method proposed by Shockley [11]. In Fig. 1 is shown the test structure, designed with dimensions as follows: the different spacing d between five rectangular N+ contacts regions are 25, 50, 75, and 100 μm. The contact length L and width Z are 10 and 50 μm, respectively.

The fabrication process of the structures consisted of two main steps, the first step is to pattern the implanted a-SiC:H layers by using reactive ion etching (Micro RIE series 800). The parameters of the RIE process using CF_4 were as follows: Power was in the range from 150 to 300 W, and the pressure was 150 mTorr. The etch rate and the selectivity of a-SiC:H etchant for defining patterns using positive photoresist were extracted at the nonpatterned region by dividing the etched film thickness by the etch time. Before the second step, a 10% HF dip was used to remove the native oxide on a-SiC:H films, then the second step follows with the deposition and patterning of aluminum for the contacts by using an Al-etch solution (5% of HNO_3, 75% of H_3PO_4, and 5% of CH_3COOH and H_2O dilution at 85 °C).

Finally, the Al/a-SiC:H samples were annealed in dry N_2 atmosphere at temperature $T_a = 350$ °C with an interval of 1 h. The particular temperature was chosen to avoid emission of hydrogen bonds that deteriorates the quality of the films [9, 10], and also, to use those films in a postprocess to integrate the optoelectronic and electronic devices on silicon wafers.

The current–voltage characteristics I–V of the Al/a-SiC:H n-type structures were measured in dark conditions with the use of a programmable voltage source (2400C) and an electrometer (6517A) from Keithley.

Table 1 Characteristic of deposition parameters in a-SiC:H films.

sample	carbon (x)	thickness (μm)	E_g (eV)
Z	0.75 (CH_4)	0.45	1.7 ± 0.2
B2	0.75 (C_2H_2)	0.55	2.2 ± 0.2
U1	0.96 (C_2H_2)	0.94	2.4 ± 0.2

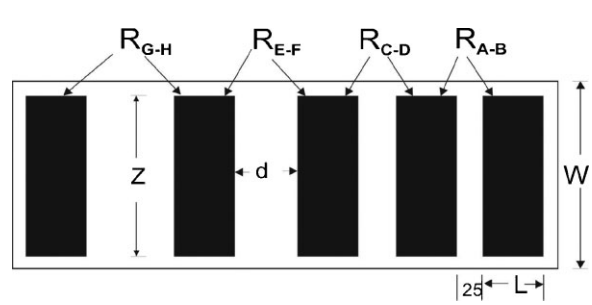

Figure 1 Test structure (TLM) used to determine the specific contact resistance, the distance d is in μm.

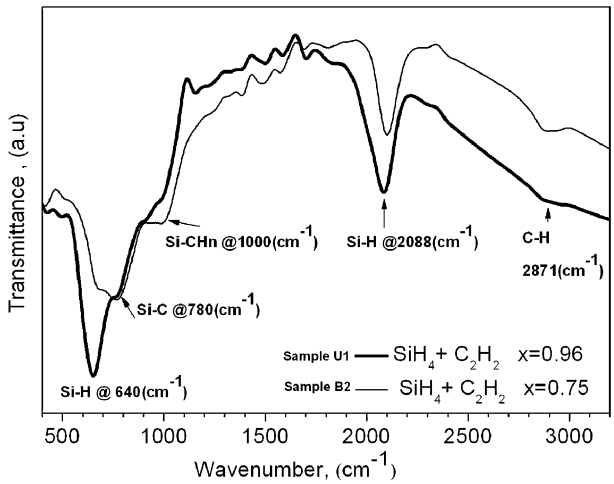

Figure 2 Infrared spectra for undoped a-SiC:H films with different $x = 0.75$ and 0.96, samples B2 and U1.

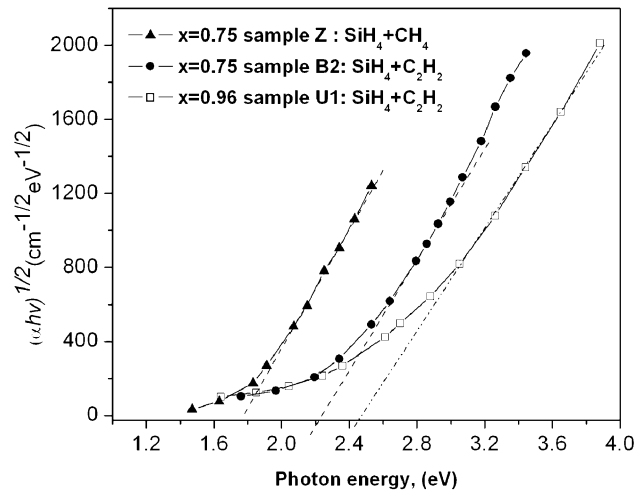

Figure 3 Changes in the optical bandgap E_g as a function of x ratio.

3 Experimental results and discussion

3.1 Films The IR absorption spectra of the samples studied are shown in Fig. 2. It is seen clearly that the peak of the stretching mode of Si–H at $k = 2\,088\ \mathrm{cm}^{-1}$ changes with x. The spectra show the typical band related with Si–C at $k = 780\ \mathrm{cm}^{-1}$, the C–H stretching band around $k = 2871\ \mathrm{cm}^{-1}$ and Si-CH_n assigned to $k = 1\,000\ \mathrm{cm}^{-1}$, these peaks are similar to those reported in Refs. [12, 13] and are the typical bonds for SiC films.

The transmission spectra measurements in the visible-near-UV region were used to determine the optical gap (E_g) in undoped layer by means of a Tauc extrapolation plot, according to

$$(\alpha h\nu)^{1/2} = B(h\nu - E_g), \tag{1}$$

where h is Planck's constant, α the absorption coefficient, ν the radiation frequency, E_g the optical band gap, and B is the slope.

Figure 3 shows the optical bandgap for undoped a-SiC:H films in the range 1.7–2.4 eV and is directly related to the gas ratio x and precursor gas. As the carbon content increases the optical bandgap increases, these results are observed in Ref. [15]; and are similar to those in Ref. [16], where the carbon content is higher in films obtained with C_2H_2 than in films obtained with CH_4. The sample deposited with C_2H_2, resulted in a large optical gap. The E_g was characterized in order to have values in the visible range for applications in light emitters and to have optimal values in the formation of barrier Al/a-SiC:H. An improvement of almost 30% was noted by changing the source gas from CH_4 to C_2H_2. Therefore, in this study, C_2H_2 is used as the carbon source in place of CH_4 to get a larger bandgap ($x = 0.96$, sample U1).

The dry etching was characterized prior to fabricating the test structures. The etch rate of a-SiC:H film is between 446 and 741 nm/min. A standard photoresist layer was used as a mask for the undoped a-SiC:H films.

Figure 4 shows the etch rate of silicon carbide films and photoresist as a function of power. The selectivity resulted in a value of 2.3, which means that the etch rate of the films is substantially higher than that of photoresist. The etch rate is higher than reported in Ref. [17] where wet etching was used and is similar to data reported in Ref. [18] for a RIE technique.

3.2 The metal/ a-SiC:H interface For a-SiC:H doped films uniform doping and therefore a constant resistivity ρ_s in the implanted layer is assumed. The total resistance R_T between two contacts is given by Eq. (2) [11]

$$R_T = \frac{\rho_s d}{Z} + 2R_c, \tag{2}$$

where R_c is the contact resistance and the slope (ρ_s/Z) is the sheet resistance R_s. The parameters Z and d are shown in

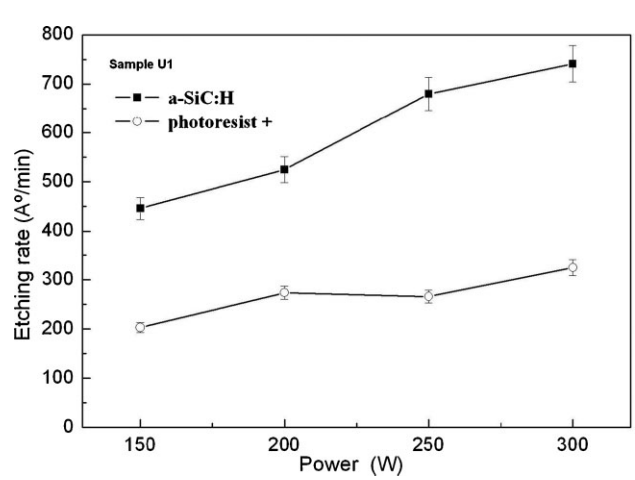

Figure 4 The etch rate for undoped a-SiC:H films prepared with (C_2H_2 at $x = 0.96$) versus power.

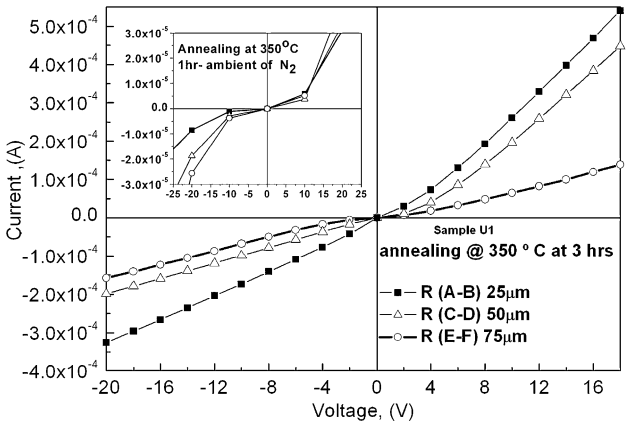

Figure 5 *I–V* characteristics of Al/a-SiC:H n-type at 350 °C under treatments of 3 h. The symbols refer to the three different distances *d* between electrodes. The insert shows the behavior of a Schottky diode for the samples after 1 h of annealing.

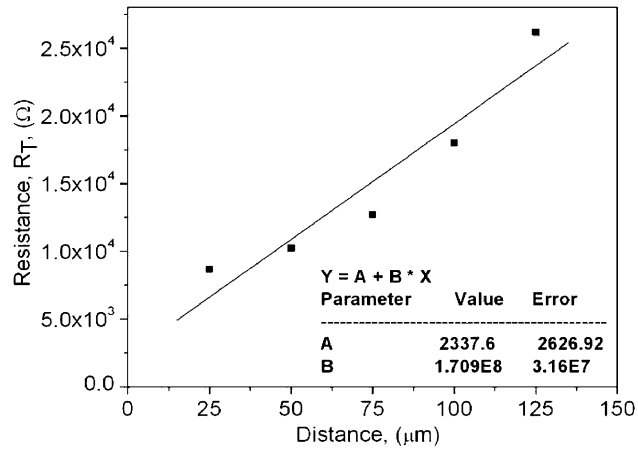

Figure 7 The resistance R_T as a function of spacing contacts *d*, which is used to determine of sheet resistance R_s and contact resistance R_c.

Fig. 1. Figures 5 and 6 show *I–V* characteristics of the sample U1 thermally treated at 350 °C under annealing steps of 1, 3, and 5 h. After 1 h a Schottky behavior is obtained in the interface metal/a-SiC:H. After 3 h near-ohmic behavior was observed, however, the goal of this study is to convert from Schottky to ohmic behavior keeping temperature constant and increasing the annealing time.

As is observed in Fig. 6 the ohmic behavior was obtained at 5 h of annealing time. These results are expected because implantation introduces disorder into the films and a gradual recovery is achieved by annealing. The optimum annealing time without further degradation due to hydrogen evolution in this study is 5 h. This time might appear large, but is comparable with Ref [19] where thermal treatments are performed for p-type a-SiC:H using Al for electrical contacts, and even less than the time reported to obtain ohmic contacts in SiC films prepared by polymer-source CVD [14] at high annealing temperatures.

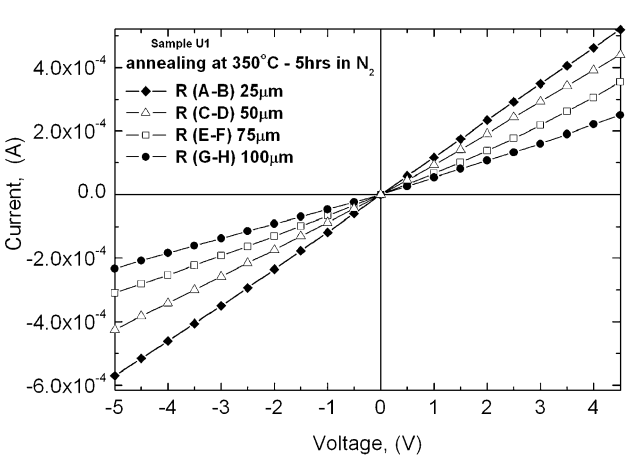

Figure 6 *I–V* characteristics of Al/a-SiC:H n-type after 5 h of annealing at 350 °C, The symbols refer to resistance for the different distances *d* between electrodes.

From Fig. 7, the plot of R_T as a function of *d* will produce a straight line with a slope ρ_s/Z and $2R_C$ is obtained from the *y*-axis intercept. The sheet resistance was obtained as $171 \times 10^6\,\Omega$ and the specific R_C value was $2.3\,\mathrm{k\Omega\,cm^2}$, the structures show a R_T from 8.6 to 26.8 kΩ for the different distances. The values of resistance in the structures obtained here are lower than reported in Ref. [14], where the authors reported high annealing temperature (1 000 °C) to obtain an ohmic characteristic. The characteristics of the contacts depend on the properties of the deposited film and on the subsequent thermal annealing process. The ohmic behavior after an annealing time of 5 h indicates that the reaction between a-SiC:H and Al is not the only reason for the ohmic behavior, it also depends on doping. As is reported in Ref. [13], where the doping could not introduce significant variation on the structural properties of the films it, however, promotes a change in the position of Fermi level that results in high electrical conductivity of the films. Moreover, at annealing temperatures $T_a > 600$ °C could allow weak emission of hydrogen in the amorphous network, which improves the electrical and optoelectronic properties of the silicon carbide amorphous films [9, 10, 13].

4 Conclusions Thin films of a-SiC:H have been obtained by PECVD at low deposition temperatures. The optical bandgap was tailored from 1.7 to 2.4 eV and it was found that it depends strongly on the film composition. The ion implantation on the silicon carbide films and the annealing time processes have been demonstrated to form good ohmic contacts using aluminum as the metal contact. The ohmic behavior was significantly improved with thermal treatments at $T_a = 350$ °C for 5 h. Further studies to relate the structural and electrical properties such as conductive mechanisms under temperature treatments are necessary. Finally, we can conclude that an ohmic behavior in n-type a-SiC:H films with a moderate contact resistance makes this material suitable for the integration of optoelectronic devices in silicon technology.

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