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R. M. Ranade
University of Arkansas, Fayetteville

S. S. Ang
University of Arkansas, Fayetteville

W. D. Brown
University of Arkansas, Fayetteville

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R. M. Ranade, S. S. Ang, and W. D. Brown
Department of Electrical Engineering
University of Arkansas
Fayetteville, AR 72701

Abstract

The effects of nitrogen trifluoride in the gas stream during deposition of semi-insulating polysilicon (SIPOS) on the electrical characteristics of undoped (SIPSO)/p-Si, and n+-SIPOS/n-Si isotype junctions were investigated. The current-voltage charateristics of undoped SIPOS/p-Si heterojunctions exhibit a strong dependence on the oxygen content of the SIPOS film and depart from a hyperbolic sine behavior as the refractive index of the SIPOS increases.. The addition of nitrogen trifluoride decreases the current density of these undoped SIPOS/p-Si heterojunctions due presumably to the oxidation/hydrolysis of SiF species into SiO_2. The n+-SIPOS formed a rectifying isotype junction o n-Si. The forward current-voltage characteristics exhibit two distinct activation energies separated by a "kink" in the forward semi-logarithmic characteristics; one below the cut-in voltage and one above the cut-in voltage. The two activation energies result from the presence of interface states in the structures. However, the forward current-voltage characteristics of the fluorinated SIPOS isotype junctions exhibit no "kink" and only a single activation energy due, presumably, to hydrogen passivating the interfacial traps during the hydrolysis process.

Introduction

Semi-insulating polysilicon (SIPOS) films have been used primarily as a surface passivant for high-voltage semiconductor devices (Matsushita et al., 1976). The finite conductivity of the undoped SIPOS film provides a field-shield effect for the passivated surfaces; yet the conductivity is low enough that leakage current through the film is reasonably low for many device applications. Other applications include use as the insulating layer in a power SIPOS MISS device (Ang, 1988) and as thin film sheet resistance SIPOS resistors in CMOS SRAMs to replace the polysilicon decoupling resistors (Ong et al., 1991).

Assumin a "mosaic" model for the SIPOS as proposed by Tarng (1978), Bolt and Simmons (1987) concluded that carrier transport through undoped SIPOS was by thermionic emission (TE) of carriers over the grain boundries at temperatures above room temperature, while carrier transport below room temperature was by thermionic field emmission (TFE) by which significant tunneling through the barrier occurs. Arnold and Karins (1983) investigated the electrical properties of doped SIPOS films and proposed a spatial fluctuation of dopant concentration to explain the transition from thermally-activated to temperature-independent conductivity at high doping concentrations. Ong et al. (1991) reported that the conductivity activation energies (0.007-0.01 eV) of arsenic doped SIPOS films are lower than those of thin film polysilicon films (0.07-0.09 eV) for the same sheet resistance of 10^5 ohms/sq. They showed that thin-film SIPOS resistors were less sensitive to changes in temperature compared to their polysilicon counterpart. Ranade et al. (1991) reported that carrier conduction in SIPOS heterojunctions on silicon is mainly controlled by the SIPOS/p-Si interface. The forward characteristics of n+-SIPOS/p-Si heterojunctions display both a low and a high field activation energy with the difference attributable to the presence of interface states at the junction.

In this paper, the effects of nitrogen trifluoride on the electrical properties of undoped SIPOS/p-type crystalline silicon, and n+-SIPOS/n-Si isotype junctions are reported.

Materials and Methods

Boron-doped and phosphorus-doped <100> silicon substrates of 2-5 ohm-cm were used for undoped heterojunctions and n+-SIPOS/n-Si isotype junctions, respectively. After an initial H_2O_2 and H_2SO_4 (1:2 by volume) clean, an HF dip etch was performed to remove the chemical and native oxide left on the silicon. SIPOS was then deposited on these silicon substrates. Details of the process used to deposit SIPOS film by plasma-enhanced chemical vapor deposition have been described in a previous paper (Lai et al., 1990). Briefly, SIPOS films were deposited on the silicon substrates in a parallel-plate, capacitively coupled, 13.56 MHz Reinberg-type reactor (Texas Instrument A24C) PECVD reactor using a mixture of monosilane (SiH_4) and nitrous oxide (N_20) with a varying N_2O/SiH_4 ratio of 0.1-0.4. In some depositions, 0.5 sccm of nitrogen trigluoride (NF_3) was added to the N_2O/SiH_4 mixture. A deposition power density of 25 mW cm^{-2} and a chamber pressure of 0.5 Torr were selected to maintain a stable plasma between the reactor electrodes to ensure reproducible film composition and uniformity. The thickness of the SIPOS was about 2000 Å. The refractive indices of the SIPOS films in this study varied from 1.8 to 2.9, with the refractive index of 2.9 corresponding to the N_2O/SiH_4 ratio of 0.1. The oxygen content in the SIPOS film with a refractive index of 2.9 was found to be about 15% using RBS. It should be noted that hydrolysis of SIPOS films occurs immediately after exposure to room ambient as the refractive index of the fluorinated SIPOS does not change with time after deposition.

SIPOS films were then implanted with arsenic for the n+-SIPOS/n-Si isotype junctions. The implant parameters were 1×10^{17} cm^{-2} at an implant energy of 150 keV. Annealing of the films was performed in a nitrogen ambient at 1000°C for 60 seconds in a computer-controlled Heatpulse 210-T rapid thermal processor. Rutherford backscattering (RBS) measurements revealed uniform arsenic profiles in the SIPOS film after rapid thermal annealing. The top electrode of the devices was aluminum, evaporated to a thickness of about 5000 Å in a thermal evaporator. Aluminum or silver paste was used as the ohmic contact on the backside of the samples.

Current-voltage measurements were performed using an HP4145A semiconductor parameter analyzer. Samples were placed in a MMR Technologies low temperature microprobe (LTMP-3) controlled by a MMR K-20 programmable temperature controller interfaced with a personal computer for temperature measurements.

Results and Discussion

Undoped Sipos/P SI Heterojunctions--Figure 1 shows the current density versus applied bias characteristics for a typical undoped SIPOS/p-Si heterojunction fabricated using SIPOS with a refractive index of 2.9 and without NF_3 in the deposition gas stream. The nonsymmetrical nature of the current-voltage data of the this device indicates that undoped SIPOS forms a heterojunction on p-type crystalline silicon. This is because SIPOS is n-type owing to the presence of donor states within its bandgap with the Fermi level pinned near and above the midgap (Tarng, 1978). It should be noted that the current-voltage characteristics of these undoped SIPOS/p-Si heterojunctions depart from hyperbolic sine behavior as the refractive index increases. Likewise, the current density versus applied bias characteristics of undoped SIPOS/p-Si heterojunctions fabricated using SIPOS with a refractive index of 2.9 and deposited with 0.5 sccm of NF_3 in the deposition gas stream depart from hyperbolic sine behavior. As can be seen, the forward current density of the fluorinated heterojunction is substantially lower than that of the unfluorinated, undoped SIPOS/p-Si heterojunction. Furthermore, the reverse current density saturates at a relatively low reverse bias. The addition of NF_3 during the SIPOS deposition favors the formation of SiF species (SiF, SiF_2, SiF_3, and $[SiF_2]_n$) in the SIPOS films. The open structure of the fluorinated SIPOS, due to a high concentration of the $[SiF_2]_n$ specie, favors the penetration of oxygen and water molecules into the network (Sanchez et al., 1993). As the SiF species hydrolyze, they are converted into SiO_2 in the SIPOS. Even through the refractive index of the SIPOS films deposited in the presence of NF_3 is similar to the SIPOS film deposited with no NF_3, the fluorinated SIPOS films contain a higher percentage of SiO_2 for the same amount of oxygen in the films.

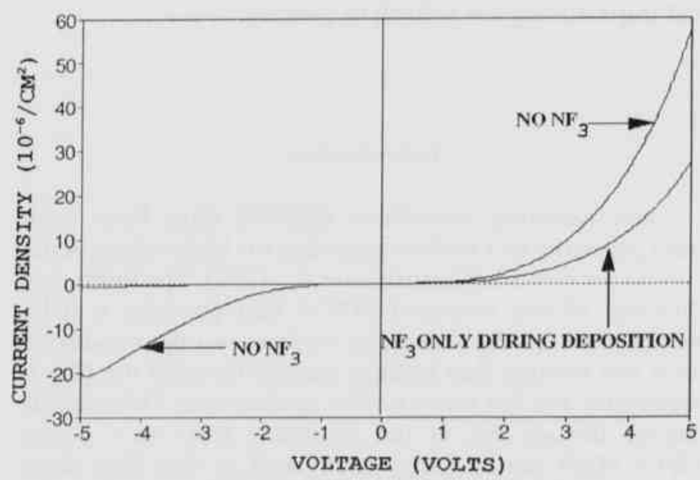

Fig.1. Current density versus applied voltage of a typical undoped and a fluorinated SIPOS/p-Si heterojunctions.

Figure 2 shows current density versus applied bias characteristics for temperatures from 260 K to 320 K for a typical heterojunction fabricated with undoped SIPOS (refractive index = 2.9) on p-type silicon. The current density increases with temperature for a given applied bias and increases with applied bias for a given temperature according to a hyperbolic sine function. At low applied biases, such that $V << 2gkT/q$, the current-voltage characteristic of the heterojunction can be expressed as (Ranade et al., 1991)

$$J = \frac{qVA^*T}{gk} e^{\frac{-\Phi_{bi}}{kt}}$$

where A* is the effective Richardson constant for silicon, g is the number of grains in series, Φ_{bi} is the barrier height, q is the electronic charge, T is the absolute temperature, k is the Boltmann constant, and V is the applied voltage. Figure 3 shows current density versus applied bias characteristics for temperatures from 260 K to 320 K of a typical heterojunction of undoped SIPOS (refractive index = 2.9) on p-type silicon with NF_3 added during the SIPOS deposition. It can be seen that the temperature dependence of its current-voltage characteristics is much weaker compared to those of undoped heterojunctions with no NF_3.

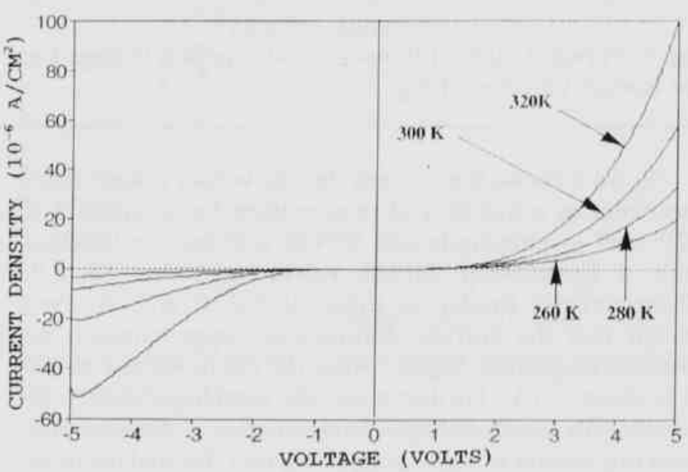

Fig. 2. Current density versus applied voltage with temperature as a parameter of a typical undoped SIPOS (R.I. = 2.9) on a p-type silicon heterojunction.

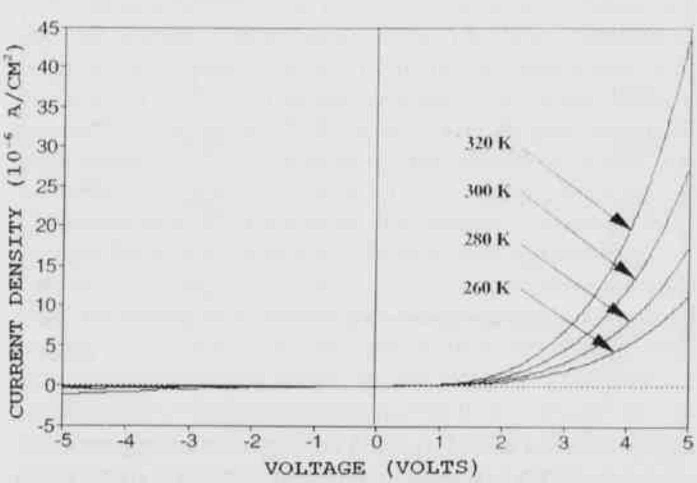

Fig. 3. Current density versus applied voltage with temperature as a parameter of a typical fluorinated SIPOS/p-Si heterojunction.

Figure 4 shows the (J/T) at V = 0.5 V versus reciprocal temperature plot for the undoped SIPOS/p-Si heterojunction diodes of Fig. 2 and Fig. 3. As shown, the (J/T) versus reciprocal temperature plot reveals two barrier heights Φ_{bi} for carrier conduction in the undoped heterojunction with no NF_3. A least-squares fit yields a Φ_{bi} of 0.27 eV for operating temperatures above 300 K and 0.04 eV below 300 K. These values are comparable to those reported by Bolt and Simmons (1987). The higher Φ_{bi} (above 300 K) suggests that carrier conduction is by thermionic emission, while below 300 K it is by thermionic field emission (Tarng, 1978), in which significant carrier tunneling through the oxide surrounding the silicon grains occurs. Furthermore, as the SIPOS refractive index decreases from 2.9 to 2.1, the high-temperature Φ_{bi} increases from 0.27 eV to 0.35 eV, while the low temperature Φ_{bi} increases from 0.04 eV to 0.07 eV. This is attributable to a thicker oxide barrier surrounding the silicon grains for a SIPOS film with a lower refractive index. Similar changes in high temperature Φ_{bi} have also been observed in bulk SIPOS films, although the high temperature Φ_{bi} in bulk undoped SIPOS films is considerably larger. The low temperature Φ_{bi} in bulk SIPOS films is very similar to that of heterojunctions since carrier tunneling is predominant. Therefore, carrier transport in the undoped SIPOS/p-Si heterojunction diodes appears to be controlled by the SIPOS/pSi interface. On the other hand, a barrier height of 0.11 eV is obtained for the undoped fluorinated SIPOS heterojunction. Thus, the undoped fluorinated SIPOS/p-Si heterojunction exhibits a single conduction mechanism for the temperature range considered. This is thought to be due to increased SiO_2 content in the fluorinated SIPOS film.

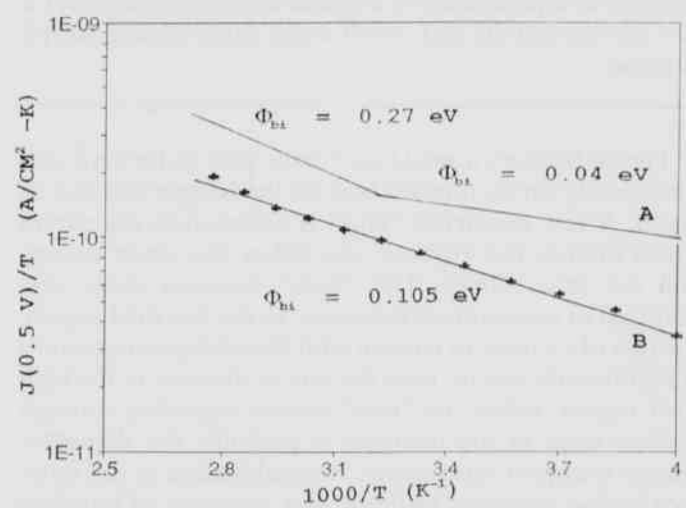

Fig. 4. (J/T) at V = 0.5 V versus reciprocal temperature of a typical undoped SIPOS (R.I. = 2.9) on a p-type silicon heterojunction.

N+-SIPOS/N-SI Isotype, Junction

Figure 5 shows current versus voltage characteristics as a function of temperature for a typical 1 X 10^{17} cm^{-2} arsenic-implanted n+-SIPOS/n-Si isotype junction with a SIPOS refractive index of 1.8. An exponential increase in current with forward bias is observed, indicating a rectifying junction. At room temperature, the cut-in voltage is about 3 V. The cut-in voltage is seen to decrease with increasing temperature because of an increasing recombination current component at the interface due to shallow states. The cut-in voltage is also found to decrease with increasing refractive index of the SIPOS (or decreasing oxygen content in the SIPOS). The reverse current was relatively temperature independence.

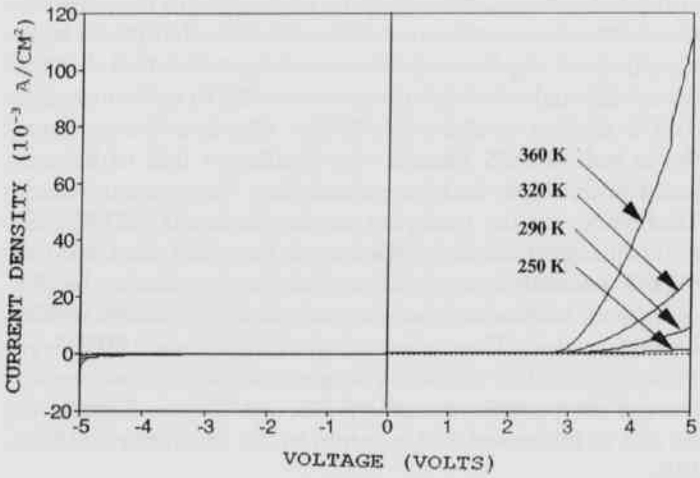

Fig. 5. Current density versus applied voltage with temperature as a parameter of a typical arsenic-implanted (1 x 10^{17} cm^{-2}) n+-SIPOS (R.I. = 1.8) on an n-type silicon isotype junction.

Figure 6 shows a semi-logarithmic plot of forward current density versus forward bias for the isotype junction of Fig. 5. A very distinctive "kink" is observed in the curves which defines two regions, one below the cut-in voltage and the other above. This "kink" becomes more pronounced as temperature increases. In the low field region, the rate of increase in current with increasing temperature is significantly smaller than the rate of increase in the high field region. Below the "kink" carrier tunneling through shallow traps at the interface is probably the dominant charge transport mechanism. Recombination at the interface is also expected owing to the presence of interface states at the junction. At higher electric fields, a temperature-activated charge transport is dominant. Hydrogen annealing of these devices passivated the shallow interfacial traps and eliminated the "kink" (Ranade et al., 1991).

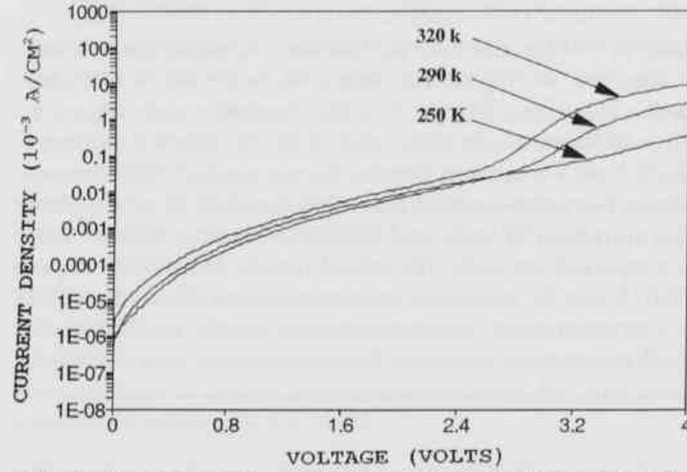

Fig. 6. Forward current density versus applied voltage for the isotype junction of Fig. 5.

Figure 7 shows the current density versus voltage characteristics as a function of temperature for a typical 1 X 10^{17} cm^{-2} arsenic-implanted SIPOS/n-Si isotype junction with a fluorinated SIPOS refractive index of 2.9. Characteristics similar to those of Fig. 5 are observed except that the current densities are approximately an order of magnitude higher. Also, the cut-in voltage at 290 K is about 0.9 V. Furthermore, the semi-logarithmic current density versus voltage characteristics of this structure does not exhibit a "kink" suggesting that the shallow interfacial traps are passivated during hydrolysis of the fluorinated SIPOS.

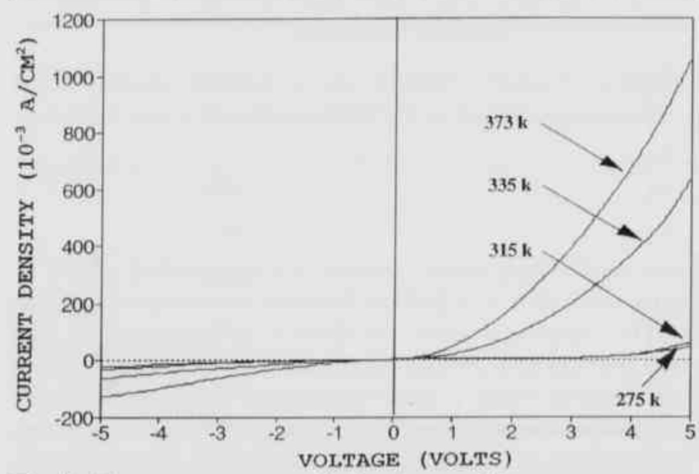

Fig. 7. Current versus applied voltage with temperature as a parameter for a typical arsenic-implanted (1 x 10^{17} cm^{-2}) n+-SIPOS (R.I. = 2.9) on an n-type silicon isotype junction.

In the reverse bias direction shown in Fig. 8, the current does not saturate with increasing bias, possibly because of space-charge induced lowering of the effective barrier height. The reverse current also increases slightly with increasing temperature, indicating a temperature-activated process. The unpassivated periphery could also contribute to this reverse current since the isotype junctions were not passivated intentionally in order to avoid any heat treatment after fabrication.

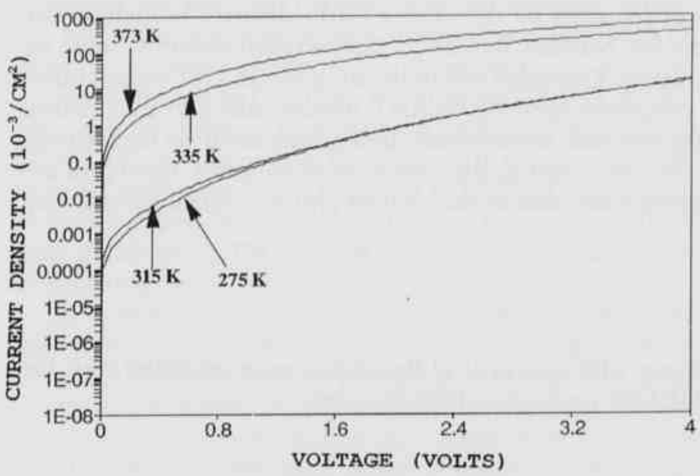

Fig. 8. Forward current density versus applied voltage for the isotype junction of Fig. 7.

Summary and Conclusions

Undoped SIPOS/p-Si heterojunctions were fabricated and electrically characterized. The J-V characteristics of these devices were compared to devices fabricated with fluorinated SIPOS. Carrier transport in these devices appears to be controlled by the SIPOS/p-Si interface. Fluorinated SIPOS heterojunctions exhibit a lower forward current density compared to un-fluorinated SIPOS heterojuntions. Furthermore, the reverse current of fluorinated devices saturates at relatively low applied bias.

The n+-SIPOS/n-Si isotype junction J-V characteristics were rectifying with a forward cut-in voltage of approximately 3 V, which decreases with both increasing temperature and refractive index of the SIPOS. The forward semi-logarithmic characteristics exhibit two distinct activation energies separated by a "kink". The low field conduction region is shown to result from shallow states at the n+-SIPOS/n-Si interface. The absence of the "kink" in the J-V characteristics of fluorinated n+-SIPOS/n-Si isotype junctions suggests that hydrogen species resulting from a hydrolysis process passivate the shallow interfacial traps.

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