Current transport properties of metal/hydrogenated amorphous silicon/GaSb structures

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Hydrogenated amorphous silicon (*a*-Si:H) has been deposited on *n*- and *p*-GaSb by the plasma glow discharge technique. The electrical characteristics of metal/*a*-Si:H/GaSb structures are presented. The current transport in these structures is dictated by the barriers at the metal/*a*-Si:H and *a*-Si:H/GaSb interfaces and the series resistance of the bulk *a*-Si:H interfacial layer. Space charge limited current in the interfacial layer gives rise to a voltage dependent resistance and increases the forward ''turn-on'' voltage. Furthermore, these structures exhibit extremely low reverse leakage currents and high reverse breakdown voltages. Significantly, rectifying junctions of *a*-Si:H/*p*-GaSb have been achieved with barrier heights of ~0.4 eV. © *1995 American Institute of Physics.*

Metal-semiconductor rectifying junctions (Schottky barriers) have been traditionally used for both materials characterization and in device structures.[1,2] Obtaining ideal Schottky contacts on III–V compounds is difficult and GaSb tends to be no exception to the rule.[1,2] The surface Fermi level in GaSb is pinned close to the valence band edge leading to extremely low Schottky barrier heights (~0.1 eV) on *p*-GaSb.[2] This results in near ohmic behavior of the metal/*p*-GaSb structure, thus limiting its applicability. The performance of GaSb-based devices are further affected by high surface leakage currents.[3] The problems of low barrier height on *p*-GaSb and high leakage currents in general can be overcome by modifying the semiconductor surface using thin interfacial layers prior to metallization. The interfacial layer can be an insulator, a larger band gap crystalline semiconductor, or an amorphous semiconductor. Amorphous semiconductors present many advantages compared to the other two,[4,5] and hence seem to be the best alternative. We have chosen *a*-Si:H for our studies and in this letter we present the electrical properties of metal/*a*-Si:H/GaSb structures. To the best of our knowledge, this is the first report on the current transport properties of such structures on GaSb.

Vertical Bridgman grown single crystal substrates of undoped *p*-GaSb and Te-doped *n*-GaSb with carrier concentrations $\sim 10^{17}\text{cm}^{-3}$ were used for our studies.[6] The back ohmic contacts on *n*- and *p*-GaSb were provided by thermal evaporation and alloying of Au-Ge (88:12) and Au-Zn (98:2) eutectic mixtures, respectively. Layers of *a*-Si:H with thickness in the range of 100–200 Å were deposited onto the front surface of the substrates using a radio frequency plasma glow discharge system[7] with rf power of 6 W/cm^2. Substrate temperatures in the range of 150–300 °C were employed. The gas used was 1% SiH_4 in hydrogen with a flow rate of 1 cc/min which was found to be optimal for obtaining high quality films. Electron diffraction studies confirmed the amorphous nature of the films. The optical energy gap of these films was found to decrease from 2.2 to 1.6 eV with an increase in deposition temperature. The decrease in band gap is caused by the decrease in hydrogen content in the layer.[8] The refractive index was between 3.8 and 4.1. Subsequently, Al and Mg top contacts of 0.25 mm diameter were evaporated onto the *a*-Si:H layers. Prior to top metal contact, the *a*-Si:H coated surfaces were rinsed in a dilute HF solution to remove any nascent oxide layer. While the Al contact is known to form rectifying Schottky junctions on *a*-Si:H,[5] Mg provides ohmic contact.[9] This helps in isolating the effects due to metal/*a*-Si:H and the *a*-Si:H/GaSb interfaces. Diodes without the *a*-Si:H interfacial layer were also fabricated for comparative studies. Some of the samples deposited at 300 °C were annealed in N_2 atmosphere at the same temperature for 1 h before metallization to investigate the effect of annealing on the electrical properties of the diodes.

The current–voltage $(I-V)$ characteristics of the Mg/*n*-GaSb and Mg/*a*-Si:H/*n*-GaSb diodes for two interfacial layer thicknesses are shown in Fig. 1(a). Similar curves were obtained for the Al/*n*-GaSb and Al/*a*-Si:H/*n*-GaSb diodes also. In the forward bias region, an increase in the turn-on voltage after the deposition of the interfacial layer can be seen. The turn-on voltage increases further with an increase in the film thickness. In the reverse bias region, the diodes with an interfacial layer exhibit excellent reverse current saturation, extremely low reverse current (~tens of nA), and high breakdown voltage (~10 V). The efficacy of the interfacial layer in preventing premature breakdown and surface leakage can be ascertained by studying reverse leakage current as a function of diode diameter at a constant reverse bias.[2] A log–log plot of the reverse current versus diode diameter for the diodes without any interfacial layer exhibited slope close to unity suggesting leakage through the surface inversion layer. In contrast, for the diodes with interfacial layer, slope nearly equal to 2 was obtained, confirming vertical current flow with negligible edge effects. Figure 1(b) shows the plots of

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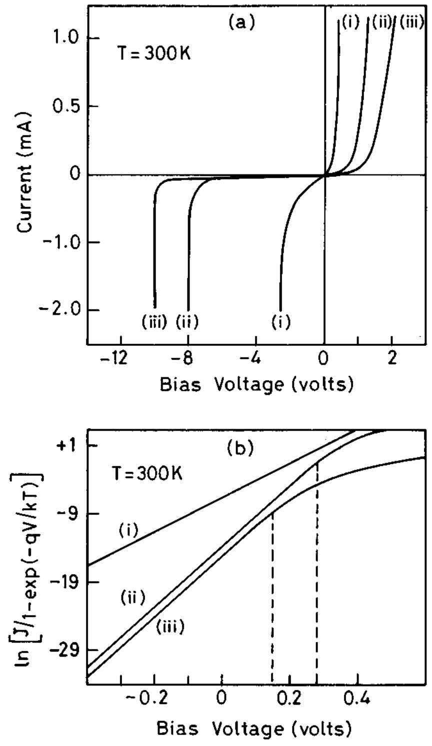

FIG. 1. (a) $I-V$ characteristics of (i) Mg/n-GaSb, (ii) Mg/a-Si:H (100 Å)/n-GaSb, (iii) Mg/a-Si:H (150 Å)/n-GaSb. (b) ln[$J/1-\exp(-qV/kT)$] vs V plots for the above three diodes.

ln[$J/1-\exp(-qV/kT)$] vs V. The curves exhibit linear behavior (as for a Schottky diode) extending from the reverse bias to the forward bias region until the series resistance due to the a-Si:H layer becomes significant. This shows that the forward $I-V$ characteristics are barrier dominated (characteristics of thermionic emission) in the low voltage regime. The forward bias at which the curves change slope depend on the thickness of the a-Si:H layer.

The $I-V$ characteristics of various diodes fabricated on p-GaSb are shown in Fig. 2 In the absence of any interfacial layer, the $I-V$ characteristics of the Mg/p-GaSb diode is ohmiclike in nature as shown by curve (i). With an a-Si:H layer of 100 Å, a nonlinear ohmic behavior is seen as depicted by curve (ii). With an increase in layer thickness, the diode characteristics improve [see curves (iii) and (iv)]. Good forward characteristics with reduction in reverse leakage current and breakdown voltage as high as 1.5 V are observed. Such $I-V$ characteristics have not been achieved until now with Schottky diodes on p-GaSb. Moreover, the reverse current in these structures is lower than the p-n junctions fabricated previously.[10]

The barrier heights (ϕ_B) and the ideality factors (n) were found for various diodes. It should be remembered that the diode structures used in our studies can have more than one barrier in series. The barrier height calculated from the $I-V$ characteristics is that of the largest one. For the diodes with Mg contact, the ϕ_B increases after the interfacial layer deposition from 0.50 to 0.67 eV and n decreases from 1.7 to 1.3. Since Mg makes ohmic contact with a-Si:H, the barrier height measured is due to the band offset at the a-Si:H/GaSb interface. For the Al/a-Si:H/GaSb diodes, the barrier height depends on the interfacial layer thickness. With layers of ~100 Å, the barrier height was approximately 0.67 eV. When the interfacial layer thickness was greater than 150 Å, the barrier heights obtained (~0.8 ev) are higher than the band gap of GaSb (0.7 eV). Thus it is clear that with Al contacts on thin a-Si:H layers, the barrier is due to the a-Si:H/GaSb interface as electrons tunnel through the a-Si:H layer via localized states. On the other hand, for the diodes with thicker a-Si:H layers, the barrier at the Al/a-Si:H interface dominates. No such thickness dependence was seen with the Mg-based diodes. Furthermore, the barrier height and ideality factor are also sensitive to post-deposition annealing. The Al/a-Si:H/n-GaSb diodes annealed after fabrication at 300 °C for 30 min exhibited values of ϕ_B and n close to that of Mg/a-Si:H/n-GaSb diodes. In fact, Al causes crystallization of a-Si:H when annealed above 250 °C due to which the Al Schottky barrier becomes nearly ohmic.[11] Thus the contribution is now from the a-Si:H/GaSb interface. Also, the diode annealed at 300 °C for 60 min before metallization exhibited a higher ϕ_B (0.86 eV) than that of similar structures fabricated without annealing. Also, n decreased from 2.1 to 1.1. The decrease in the ideality factor and saturation current density with an increase in deposition temperature and after annealing is attributed to the decrease in deep level concentration in bulk a-Si:H. These deep levels originate from the SiH$_x$ ($x=2$ or 3) centers[12] and are responsible for the Fermi level pinning at the interface. The concentration of SiH$_x$ decreases with an increase in deposition temperature.[12] Also, SiH$_x$ decomposes by annealing at 200–250 °C (Ref. 12) further reducing the deep level concentration. With a change in deposition temperature, even though the band gap of a-Si:H changes drastically, the barrier heights remain almost the same. This shows that the deep levels tend to track the conduction band edge in a-Si:H. Since the barrier heights at the metal/a-Si:H and a-Si:H/GaSb interfaces are much different, the deep levels responsible for Fermi level pinning at these interfaces are not the same. In the barrier height calculations, the Richardson constant A^* for GaSb (5.28 A cm^{-2} K^{-2}) was used first. However, when the barrier at the Al/a-Si:H interface dominates, ϕ_B thus calculated will be underestimated. In such cases, the

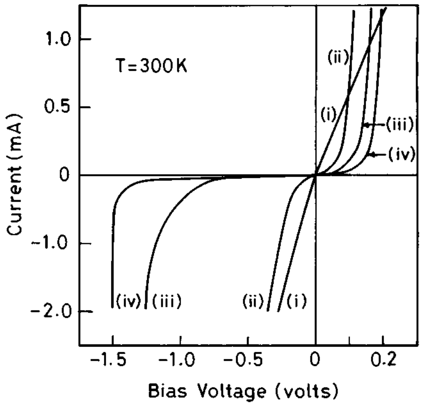

FIG. 2. (a) $I-V$ characteristics of (i) Mg/p-GaSb, (ii) Mg/a-Si:H (100 Å)/p-GaSb, (iii) Mg/a-Si:H (150 Å)/p-GaSb, (iv) Mg/a-Si:H (200 Å)/p-GaSb.

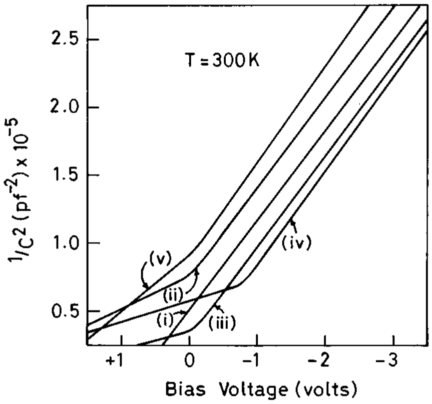

FIG. 3. $C-V$ characteristics of (i) Mg/*n*-GaSb, (ii) Mg/*a*-Si:H (150 Å)/*n*-GaSb, (iii) Al/*a*-Si:H (100 Å)/*n*-GaSb, (iv) Al/*a*-Si:H (150 Å)/*n*-GaSb, (v) Mg/*a*-Si:H (200 Å)/*p*-GaSb.

value of A^* for *a*-Si:H (96 A $\mathrm{cm}^{-2}\ \mathrm{K}^{-2}$) (Ref. 13) was used to obtain the actual barrier heights.

The steady-state $C-V$ characteristics at 1 MHz for various diodes on *n*- and *p*-GaSb are shown in Fig. 3. The Mg/*a*-Si:H/*n*-GaSb (curve ii) and Mg/*a*-Si:H/*p*-GaSb (curve v) diodes exhibit linear $1/C^2$ vs V plots with the same slope (in the reverse bias regime) as the Mg/*n*-GaSb diode (curve i), indicating the depletion region to be in GaSb. However, the intercepts on the voltage axis are offset from the intercepts of the Mg/GaSb diode due to the series capacitance of the *a*-Si:H layer, which acts as an insulator at 1 MHz. For the Al/*a*-Si:H/*n*-GaSb diodes, the depletion region extends from the *a*-Si:H layer to the GaSb substrate with an increase in reverse bias. It should be noted that in spite of the MIS like structure of the present diodes due to the high resistive *a*-Si:H layer ($\sim 10^7\ \Omega$ cm), the $C-V$ characteristics do not show accumulation or inversion regions. This is due to current flow in the bulk *a*-Si:H via localized states. As previously demonstrated by Loualiche *et al.* on *n*-GaInAs,[4] our structures can be advantageously used for FETs with the *a*-Si:H layer acting as the gate.

Lastly, it is worth mentioning that even though the current flow in the forward bias regime will reduce due to the series resistance of the *a*-Si:H layer, the same is not responsible for the increase in the turn-on voltage as depicted in Figs. 1(a) and 2. The increased turn-on voltage can be explained in terms of the space charge limited current (SCLC) in the thin *a*-Si:H layer. Injection of charge carriers into this high resistive layer results in a gradual transition from ohmic ($I \propto V$) to SCLC ($I \propto V^m$, $m=5$) characteristics with an increase in forward bias. At low potentials, the $I-V$ characteristics were found to be barrier dominated and can very well be fitted by the $I-V$ relation for a Schottky diode.[11] In the high voltage regime, strong injection of excess electrons occurs and the quasi-Fermi level moves through an appreciable energy range towards the conduction band.[14] The effect of SCLC is to decrease the effective series resistance above a certain threshold voltage drastically leading to a rapid increase in the current.

In conclusion, we have investigated the current transport properties of metal/*a*-Si:H/GaSb heterostructures. The current in these diodes are controlled by the barriers at the *a*-Si:H/GaSb and metal/*a*-Si:H junctions appearing in series with an effective resistance of the *a*-Si:H layer. From a technological point of view, since rectifying metal/*a*-Si:H contact dominates the $I-V$ characteristic in reverse bias and low forward bias due to high barrier heights, GaSb-based MESFETs with extremely low gate leakage currents can be fabricated with an interfacial layer of *a*-Si:H. Here the depletion layer extends through the *a*-Si:H layer into the bulk GaSb, allowing modulation of the channel in FETs. Furthermore, due to its ability to reduce leakage current, thin interfacial layers of *a*-Si:H can be potential surface passivants. The present surface treatment process is better than wet chemical treatments[15,16] and certainly more suitable for passivating large wafers uniformly. Due to the extremely low dark currents, the *a*-Si:H/GaSb structures can also be employed as stacked solar cells[17] of high efficiency. The structures are reproducible and highly stable. Moreover, the process of glow discharge treatment used in our studies can easily be employed for large scale device production.

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