OHMIC AND QUASI-OHMIC CONTACTS TO HYDROGENATED AMORPHOUS SILICON THIN FILMS

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An extensive study of contacts properties to undoped and doped hydrogenated amorphous silicon, undertaken in our laboratory, has shown that ohmicity and contact quality are very dependent on the reactivity of the metal and the quality of the metal / a-Si:H interface. For example, metals such as Sc, Mg or Ti form exceptionally good ohmic (very low barrier height) contacts, while others like Al, Cu, Mo or V form very poor quasi-ohmic contacts (average barrier height) to undoped films. In addition, metals such as Y, Ho, Hf or Er create fair quasi-ohmic (low barrier height) contacts to undoped films, at room temperature. The barrier height and the magnitude of current density can be adjusted to some degree not only by the proper choice of metal work function but also by changing material bulk resistivity or/and interface quality. Consequently, specific attention is devoted to these parameters which not only determine the quality of ohmic contact but also the dominant conduction mechanism across the barrier.

I. INTRODUCTION

The motivation for this extensive study has been driven by the usage of thin film transistors (TFT's) as the switching device in large area liquid crystal flat panel displays (LCD's) [1]. Consequently, the aim of this work is to find the best source/drain metallization for hydrogenated amorphous silicon (a-Si:H) TFT's, especially, since the quality of source/drain (ohmic or quasi-ohmic) contacts is one of key factors affecting the TFT's performance [2,3]. Indeed, a high specific metal source/drain contact resistance will strongly affect the device transconductance at low voltage, affecting liquid crystal charging. In addition, if the usage of a heavily doped (n^+) layer at the metal source or drain / a-Si:H interface can be avoided, this will simplify the processing, eliminate a source of eventual cross-contamination, decrease the capital equipment expense and enhance safety during the fabrication of TFT's. This study should also help in device and circuit modeling.

In this paper the different metallizations on undoped and doped HOMOCVD and PECVD a-Si:H film are described. The ohmicity and properties of various metal / a-Si:H interfaces on an asymmetric sandwich diode structure are discussed in this paper. A similar structure has already been used successfully for c-Si and GaAs contact studies [4].

II. EXPERIMENTAL

Intrinsic n-type undoped or doped a-Si:H films about 1 μm thick of comparable electronic quality (comparable electrical and optical properties) were grown by both homogeneous chemical vapor deposition (HOMOCVD) and plasma enhanced chemical vapor deposition (PECVD) techniques, on glass substrates coated with molybdenum (Mo); and a heavily doped a-Si:H layer about 300 Å thick was used to ensure low resistance of the back contact to the Mo. Both CVD techniques have been described in the literature [5]. Various metal top contacts of 0.15μm thickness were deposited by vacuum evaporation (10^{-7} Torr) using an electron-beam gun source on a chemically etched surface (buffered HF). However, even under this condition the metal and a-Si:H are not in intimate contact. There inevitably exists a very thin (<5 Å) interfacial oxide layer. The top contact areas were defined by stainless steel masks. As was already mentioned, the nature and ohmicity of top metal / a-Si:H

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interface has been studied in an asymmetric sandwich configuration [4]. The ratio of top to back contact areas was between 10^3 and 10^4; and the depletion width of the back contact barrier Mo/n^+ is sufficiently thin, because of high dopant concentration, so that this contact presents very little voltage drop for total current flow. Consequently, in this configuration the top metal contact will mostly determine the contact properties, i.e., current density (J) - applied voltage (V) characteristics. Indeed, the J - V curves, taken using an HP 4140B pico-ammeter interfaced with IBM PC-XT, scale with top contact area. The chemical composition of a-Si:H films was determined using secondary ion mass spectroscopy (SIMS, Cameca IMS - 3F). A scanning auger microprobe spectrometer (AES, Perkin Elmer) was used in conjunction with argon ion sputtering to obtain elemental depth profiles of various contacts. The nuclear back scattering (NBS) technique was used for checking for silicide formation at the interfaces at room temperature. A detailed description of these techniques can also be found in the literature.

III. BACKGROUND

Phenomenologically, a metal / a-Si:H contact is defined as ohmic if its current density - applied voltage characteristic obeys Ohm's law, i.e., the J - V characteristics for both polarities should approximate a straight line going through the origin. Ideally, the contact resistance of such metal contact should be negligible relative to the bulk (space-charge-limited) or spreading resistance of a-Si:H layer. But this is rarely achieved in practice and, from a practical point view, a satisfactory ohmic contact is one that does not perturb device performance to any significant extent. In other words, the low-resistance metal contact (conventionally classified as ohmic contact) to a-Si:H is usually acceptable if it can supply the required current density for normal mode of operation with a voltage drop that is sufficiently small compared with the voltage drop across the active region of an a-Si:H device, even though the J-V curve of such a contact is not strictly linear. Indeed, such contact must serve purely as a means for getting current into and out of the semiconductor.

Moreover, besides the low contact resistance between the metal source/drain contacts and the channel region of a-Si:H TFT these contacts should have: (a) good adhesion properties during formation, processing and service; (b) high scratch resistance; (c) low compressive stress in order not to cause excessive stress in the underlying layer; (d) good electrical, mechanical and thermal stability; (e) reproducible, economical means of preparation; (f) resistace to oxidation or corrosion and (g) compatibility with interconnection technology.

The three simple methods to achieve an ohmic contact are the following: (1) a good choice of the metal with the proper relative Fermi level (the metal work function, ϕ_m, must be equal to or smaller than the a-Si:H electronic affinity, $\chi_s \cong 4.0$ eV) so that the barrier is small for thermally excited currents; (2) introduction on the a-Si:H layer side of high densities of recombination - generation centers, by damaging the surface, for example; and (3) deposition at the metal / a-Si:H interface a very heavily doped ($>10^{21}$ atoms/cm^3) a-Si:H layer several hundred angstroms thick. Unfortunately, the barrier height is relatively insensitive to the metal work function [6,7,13] and the presence of surface states make it virtually impossible to engineer an accumulation ohmic contact, especially for n - type wide band gap amorphous materials. In addition, the fabrication of recombination - generation centers cannot be well controlled and may cause other problems in TFT's performance. It is clear, therefore, that if the single element metallization does not meet the contact requirements, this leaves the last technique as the only practical one, and which therefore is widely used in the present TFT's technology. Although the contact on heavily doped a-Si:H is of low resistance its J - V characteristics can still be nonohmic. All three methods are presently under investigation. However, the applicability of the first and last approaches will be discussed in this paper.

The electrical quality of any metal contact to an semiconductor can be characterized by its specific contact resistance (R_{sc}, in Ωcm^2) sometimes called contact resistivity, which serves as a measure of the ohmic or rectifying behavior of a metal / semiconductor barrier under operations conditions [8 – 10]. R_{sc} is the product of the contact resistance and the contact area. Since it is the contact resistance, and not the contact resistivity that governs device behavior, it is tempting to divide the R_{sc} value by the contact area to obtain the contact resistance. This is only correct in our sandwich configuration where the current flows vertically. However, in the real TFT configuration the current flows laterally in the channel; therefore, the planar configuration should be also studied in order to determine if the contact length is equal to the transfer length [9,11]. For example, it is clear that if R_{sc} is very low, most of the current will transfer near the edge of the metal drain contact (current crowding will take place) and the transfer length will be smaller than the contact length; if R_{sc} is high (as in the case of an a-Si:H film) the transfer length can or will be large and eventually is equal to the contact length (i.e., the effective area is automatically equal to the total contact area). The experimentally observed [14] current crowding at the drain contact in a-Si:H TFT's is caused by the fact that the resistivity of undoped or heavily doped layer is remarkably higher than that of the metal layer. Because the concept of the transfer length only applies to the planar configuration [9,11], this concept will be not discussed in this paper. The transfer length measurements in the planar configuration will be the subject of a separate publication.

IV. EXPERIMENTAL RESULTS

The physical and chemical properties of metal / HOMOCVD undoped a-Si:H interface have been studied by using SIMS, AES and NBS techniques. The chemical composition for a typical a-Si:H film is shown in Fig. 1a. It should be noted that the phosphorous concentration in the heavily doped n^+ - layer forming the back contact is around 10^{22} atoms/cm^3 so that the resulting Schottky barrier (with very narrow depletion region, W<100 Å) is easily penetrated by deep-gap-state-assisted multistep tunneling of carriers between the metal and the conduction band of a-Si:H film.

The chemical reactivity between a-Si:H and the contact metals, i.e., intermixing and silicide formation, has been checked by NBS, Fig. 1b. From this study it can be concluded that both the absence of silicide formation for such metals as Mo, V, Ti or Al and the presence of metal silicides for other metals like Sc, Ho or Hf have been detected, even though the contacts were all prepared at room temperature. In general, the metal silicides formed after annealing improve the quality of this interface and decrease its specific contact resistance. This will also be discussed in the separate paper.

The sharpness and quality of each metal / a-Si:H interface has been studied by AES. An example of AES depth profiles (depth resolution is about 10 Å) for as deposited Ti on a-Si:H layer is given in Fig. 1c. The Ti / a-Si:H interface appears to be relatively sharp and contain small quantities of interfacial oxide (AES detection limit is < 1 at.%). If this interfacial oxide layer is thick enough it can influence the contact electrical properties and inhibit the metal / a-Si:H intermixing and silicide formation, at room temperature.

The electrical properties of contacts on undoped and doped a-Si:H have been measured at room temperature. Typical current density versus applied voltage characteristics for different metallization on HOMOCVD and PECVD undoped a-Si:H films are shown in Fig. 2.

Although the variation of potential barrier height (ϕ_b) with the metal work function (ϕ_m) is not simple and linear, to some extent ohmic or quasi - ohmic behavior is observed for metals having ϕ_m lower than the χ_s of the a-Si:H film. Moreover, from our experimental findings it has been established that for the single element metallization: (a) an ohmic contact is observed if $0<\phi_b/E_g<0.3$; (b) a quasi - ohmic contact can be achieved if $0.3<\phi_b/E_g<0.5$; and (c) a Schottky diode is formed if $0.5<\phi_b/E_g<1.0$;

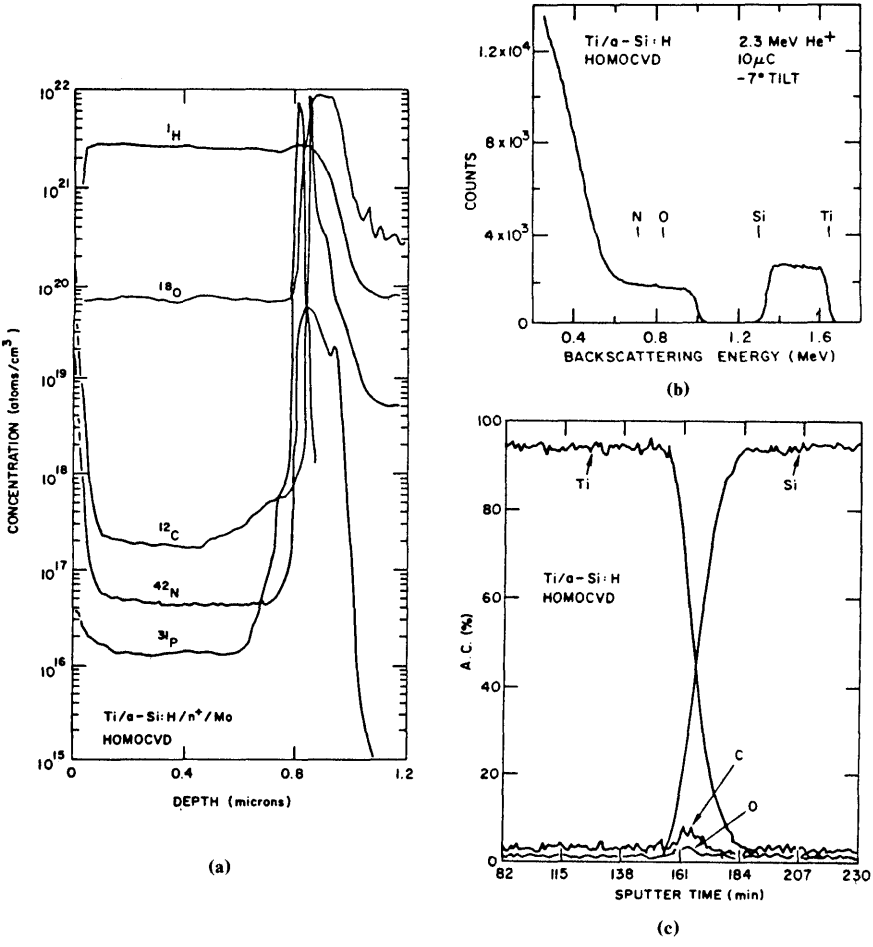

FIGURE 1a, b and c. SIMS (a), Backscatering (b) and Auger (c) depth - composition profiles of as deposited Ti on undoped HOMOCVD a-Si:H film.

these conditions are only valid, at room temperature, for as deposited metals on undoped a-Si:H layers. Consequently, metals such as Sc, Mg or Ti form exceptionally good ohmic contacts, while others like Al, Cu, Mo or V form very poor quasi-ohmic contacts to undoped films. Metals such as Y, Ho, Hf or Er create fair quasi-ohmic contacts to undoped films, at room temperature.

The ohmicity of metal / a-Si:H interface can be tremendously improved by increasing the conductivity of a-Si:H layer, i.e., by increasing the doping level in the film. The evolution of J - V curves with doping is given in Fig. 3 for 1 μm thick PECVD a-Si:H films.

It is evident from these figures that the ohmicity of the contact is strongly dependent on doping density and the surface state pinning of the Fermi level preventing the formation of a low resistance contact to undoped a-Si:H layer can be overcome if the a-Si:H layer is heavily doped ($N_{eff} > 10^{21}$ cm^{-3}). This is

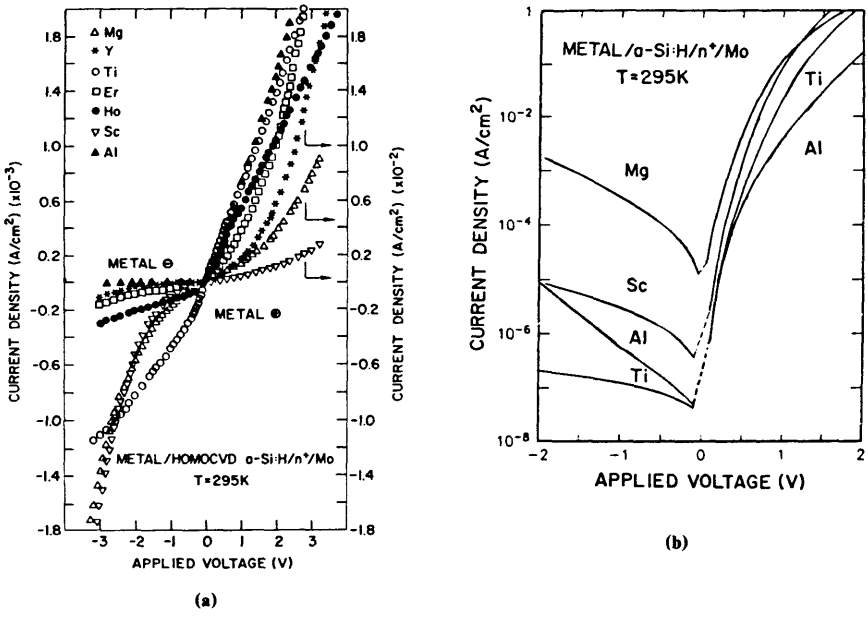

FIGURE 2a and b. Current density - applied voltage characteristics of different metals on (a) HOMOCVD and (b) PECVD undoped a-Si:H films at room temperature.

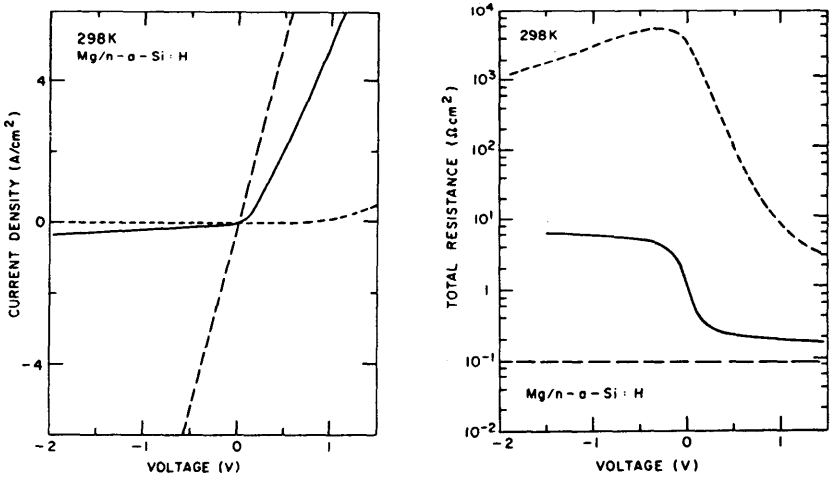

FIGURE 3a and b. Influence of the phosphorous doping on: (a) current density - applied voltage characteristics; (b) specific contact resistance of Al/Mg / a-Si:H interface.

because even if a potential barrier exists for doped films, the depletion width of this barrier, being dopant concentration dependent, is sufficiently thin that the deep-gap-state-enhanced multistep tunnellig / recombination-generation process takes place at the metal / n^+ / a-Si:H interface and an increase of several orders of magnitude in the junction reverse current density is observed. Thus the barrier becomes almost transparent for carriers at higher doping level, and the contact requires very little voltage drop for current flow which is, of course, a desirable property for source/drain metallization.

V. DISCUSSION

The impossibility of achieving a good low resistance ohmic contact to an undoped high resistivity ($>10^{10}$ Ωcm) a-Si:H layer by simple evaporation of low work function metals (Al, Cr, Mo, ...) strongly suggest the presence of a large density of surface and near interface deep gap states (arising, for instance, from dangling bonds). Indeed, the existence of such states has been already well established in different laboratories [1,5 – 7]. These negatively charged states at or near the interface produce a depletion barrier in the a-Si:H even with metals of low work function. For sufficiently low doping, this barrier will be low and spreadout, and conductance will be dominated by bulk resistance, which is not strictly ohmic (due to space charge injection effects) but is relatively symmetric. For higher a-Si:H doping, the barrier formation is more important, and behavior is more like that of a Schottky diode. At even higher doping, the barrier becomes very narrow, allowing tunneling from the metal. In this regime, the junction resistance decrease more rapidly than the bulk resistance with increased doping, and the structure again appear ohmic.

Minority carriers can also play a role, as has been described earlier [12]. In the forward direction, hole current can be injected from the metal, especially for contacts with higher barriers. Also in the reverse direction, tunneling may be supplemented by generation current in the case of heavy doping in the a-Si:H.

More important, probably, than work function in the case of contacts on real (oxidized) a-Si:H is the reactivity of the metal. The getter action of such metals as Ti, Mg or Sc (which must be protected by an Al layer) in reacting with a thin oxide layer can cause a significant reduction in the density of interface states, thereby lowering the depletion barrier and making a more ohmic contact. This effect can be enhanced with annealing.

A given metal can be judged on its ability to make a good low resistance contact to a-Si:H by examining the value of the contact resistance. The lower the resistance, the better the contact; zero would be ideal. From our experiments it is obvious that this does not happen for a-Si:H layers (Fig. 4). Nevertheless, it can be concluded that, on the one hand, the R_{sc} is a weak function of ϕ_m, for a given doping level, and and on the other hand is a strong function of dopant concentration for a given metal at room temperature. For example, R_{sc} decreases only by 3 orders of magnitude as ϕ_m decreases from 4.7 eV to 3.5 eV; in contrary, the decrease by 6 orders of magnitude has been observed for doped samples of thickness about 1 μm (Fig. 4). Therefore, the Mg is better than Al, but the improvement is more dramatic when n is increased to n^+ in the a-Si:H. In the best case these improvement are combined in the Al/Mg/n^+ contact which for a contact area of 100 μm x 10 μm has a resistance of only 10^4 Ω, which is negligible in comparison with the channel resistance ($R_{off}>10^{13}$ Ω and $R_{on}>10^7$ Ω) of a 100 μm W x 10 μm L a-Si:H (t_f = 0.2 μm) TFT; this is very helpful in reducing parasitic resistance in a-Si:H n-channel TFT's.

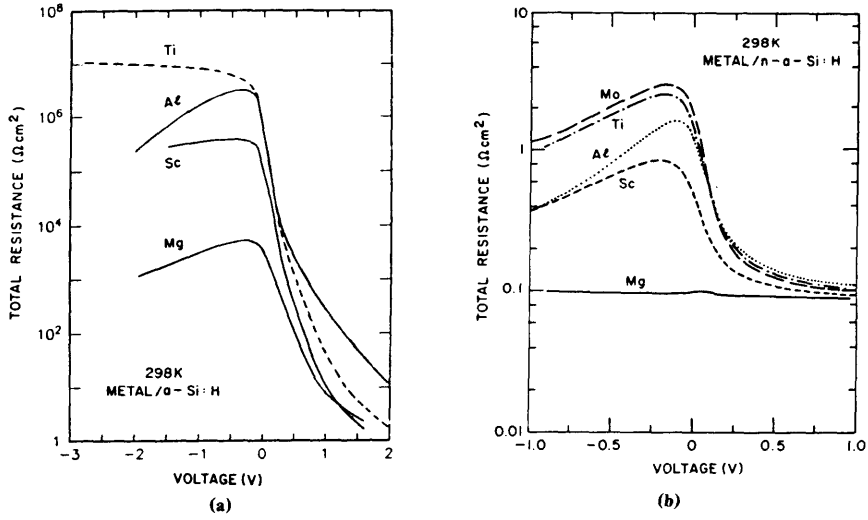

FIGURE 4a and b. Specific contact resistance, at room temperature, as a function of applied voltage of various metals on PECVD (a) undoped and (b) doped a-Si:H films.

VI. CONCLUSION

A systematic study of contacts on a-Si:H shows that ohmic behavior and contact resistance can be related to metal work function, but only weakly. More important in determining contact behavior are metal reactivity and a-Si:H doping level. A clarification of the mechanism in the case of reactive metals would require new analytical technique to confirm chemical changes within 10 Å of the interface. For device purpose, the best contact which we have found is the Al/Mg/n^+ system.

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REFERENCES

1. MRS Symposia Proc. "Comparison of Thin Film Transistor and SOI Technology", vol. 33, eds. H.W. Lam and M.J. Thompson, North - Holland, New York, 1984.

2. M. Matsumura, S.I. Kuno and Y. Uchida, J. de Physique, 42 , C4 - 519 (1981).

3. R.E.I. Schropp, J.W.C. Veltkamp, J. Snijder and J.F. Verwey, IEEE Trans. Electron Devices, ED-32 , 1757 (1985).

4. R.H. Cox and H.Strack, Solid-State Electron., 10 , 1213 (1967).

5. Semiconductors and Semimetals, vol. 21 "Hydrogenated Amorphous Silicon", part A "Preparation and Structure", ed. J.I. Pankove, Academic Press, New York, 1984.

6. J. Kanicki, C.M. Ransom, W. Bauhofer, T.I. Chappell and B.A. Scott, J. Non-Cryst. Solids, 66 , 51 (1984).

7. C.R. Wronski and D.E. Carlson, Solid State Comm., 23 , 421 (1977).

8. C.Y. Chang, Y.K. Fang and S.M. Sze, Solid-State Electron., 14 , 541 (1971).

9. H.H. Berger, J. Electrochem. Soc., 119 , 507 (1972).

10. A.Y.C. Yu, Solid-State Electron., 13 , 239 (1970).

11. G.K. Reeves and H.B. Harrison, IEEE Electron Device Let., EDL-3 , 111 (1982).

12. J. Kanicki, Minority carrier injection and series resistance effects in hydrogenated amorphous silicon Schottky barrier diodes, Mat. Res. Soc. Symp. Proc., vol. 49, 101 (1985).

13. J.I.B. Wilson and P. Robinson, Solid - State Electron., 21 , 489 (1978).

14. M.J. Powell and J.W. Orton, Appl. Phys. Lett., 45 , 171 (1984).