Indium oxide diffusion barriers for Al/Si metallizations

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Indium oxide (In_2O_3) films were prepared by reactive rf sputtering of an In target in O_2/Ar plasma. We have investigated the application of these films as diffusion barriers in ⟨Si⟩/In_2O_3/Al and ⟨Si⟩/$TiSi_{2.3}$/In_2O_3/Al metallizations. Scanning transmission electron microscopy together with energy dispersive analysis of x ray of cross-sectional Si/In_2O_3/Al specimens, and electrical measurements on shallow n^+-p junction diodes were used to evaluate the diffusion barrier capability of In_2O_3 films. We find that 100-nm-thick In_2O_3 layers prevent the intermixing between Al and Si in ⟨Si⟩/In_2O_3/Al contacts up to 650 °C for 30 min, which makes this material one of the best thin-film diffusion barriers on record between Al and Si. (The Si-Al eutectic temperature is 577 °C, Al melts at 660 °C.) When a contacting layer of titanium silicide is incorporated to form a ⟨Si⟩/$TiSi_{2.3}$/In_2O_3/Al metallization structure, the thermal stability of the contact drops to 600 °C for 30 min heat treatment.

An electrical contact to a semiconductor must fulfill two major conditions: the contact has to satisfy a prescribed electrical characteristic and this characteristic must be stable in time. It is an important and serious problem to assure the stability of the conventional Al-Si metallization during the thermal cycles it is exposed to in past-metallization processing. To achieve stable and reliable contacts, diffusion barriers are indispensable in present very large scale integrated contact technologies.[1-3] Electrically conducting RuO_2[4-9] and $Mo_{1-x}O_x$[7,10,11] films have recently emerged as potential candidates for diffusion barriers. These layers were shown by electrical measurements on Si shallow junctions and backscattering spectrometry to be excellent diffusion barriers between Al and Si up to 600 °C annealing for 30 min.

In this letter we report on the diffusion barrier properties of reactively sputtered In_2O_3. Since In_2O_3 is electrically conductive and optically transparent, its potential applications as a diffusion barrier in optical devices are very promising. The In_2O_3- and Sn-doped In_2O_3 films are already very well known for their use as infrared mirrors, antireflective coatings, and electrodes in photoconductive devices and optical waveguides (see, for example, Refs. 12–14).

The deposition of the films was performed in a rf reactive sputtering system using a planar magnetron-type circular cathode of 7.5 cm diameter. The substrate holder was placed about 7 cm below the target and was neither cooled nor heated externally. The sputtering chamber was evacuated to a base pressure of about 4×10^{-7} Torr prior to sputter deposition. The total initial gas pressure was adjusted with a variable leak valve and monitored with a capacitive manometer prior to striking the discharge.

In_2O_3 films were deposited in an O_2/Ar gas mixture with a total initial gas pressure of 10 mTorr. The relative partial pressure of oxygen in the premixed gas was 50%. The substrate bias was -50 V. Samples with the configuration ⟨Si⟩/In_2O_3/Al and ⟨Si⟩/Ti $Si_{2.3}$/In_2O_3/Al were prepared to test the diffusion barrier properties of In_2O_3 films. The metallizations were deposited on ⟨100⟩ Si wafers and on shallow n^+-p junctions formed by implantation of As^+ into ⟨100⟩ Si wafers. Prior to loading into the sputtering chamber, the silicon substrates were etched with diluted HF. The thickness of In_2O_3 films is about 80–100 nm. Aluminum overlayers (500 nm) were deposited on top of In_2O_3 films without breaking the vacuum in the sputtering system. The silicide films were sputtered from a composite $TiSi_2$ target in Ar gas. The films have a nominal composition of $TiSi_{2.3}$, as determined by backscattering spectrometry. The thickness of $TiSi_{2.3}$ is about 30 nm. The samples were annealed in a vacuum furnace at a pressure below 5×10^{-7} Torr in the temperature range 400–700 °C for different time durations. The thermal stability of contacts was analyzed by electrical measurements. Scanning transmission electron microscopy (STEM) and energy dispersive analysis of x rays (EDAX) were used to obtain chemical information and depth distribution of elements. To prepare cross-sectional specimens, the samples were first glued together face to face, followed by mechanical thinning to 10 μm. Finally argon ion milling at liquid-nitrogen temperature was used to thin the specimen to electron transparency. Shallow n^+-p junction diodes with a 300 nm junction depth, about 10^{21} As atoms cm^{-3} surface concentration, and 100×100 μm^2 contact areas were used for electrical measurements. The contact metallizations were delineated by the lift-off technique.

The In_2O_3 films are polycrystalline as determined by x-ray Read camera diffraction. The resistivity of as-deposited In_2O_3 films is about 10 Ω cm and drops to 270 $\mu\Omega$ cm after annealing at 400 °C for 1 h in vacuum or forming gas.

Figure 1(a) shows a STEM micrograph and Fig. 1(b) shows an EDAX depth profile obtained from an as-deposited ⟨Si⟩/In_2O_3/Al sample. The reference points on the cross-sectional specimen show where EDAX signals were collected. Their numbers on the STEM micrograph [Fig. 1(a)] refer to the corresponding position in the EDAX depth profile [Fig. 1(b)]. The depth resolution of this method is about 10 nm and the detection limit for elements present in our sample is about 2 at. %. The STEM micrograph and the EDAX profile of the Si/In_2O_3/Al sample annealed at 600 °C for 30 min are presented in Figs. 1(c) and 1(d), respectively.

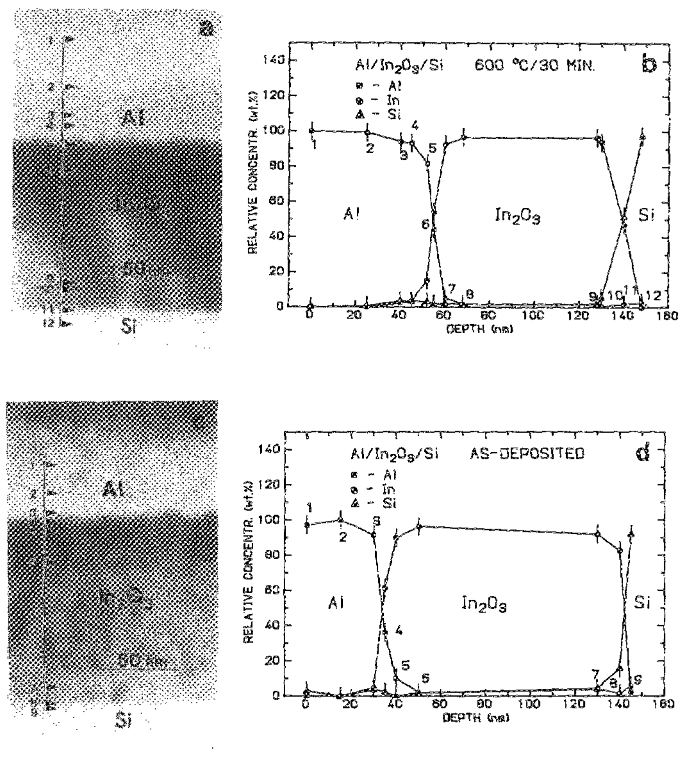

FIG. 1. (a) STEM micrograph and (b) an EDAX depth profile of an as-deposited Si/In_2O_3/Al sample. (c) STEM micrograph and (d) EDAX depth profile after annealing the sample at 600 °C for 30 min.

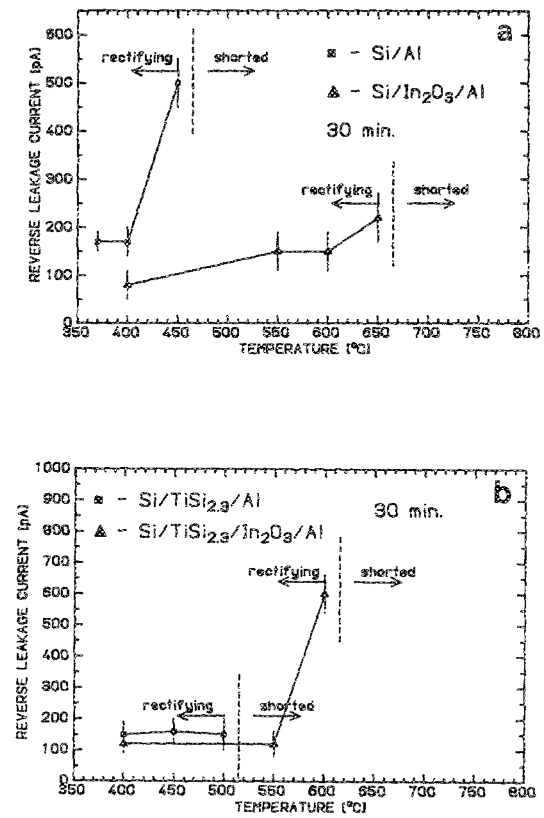

FIG. 2. Reverse leakage current as a function of annealing temperature for (a) a ⟨Si⟩/Al and ⟨Si⟩/In_2O_3/Al sample, and for (b) a ⟨Si⟩/$TiSi_{2.3}$/Al and ⟨Si⟩/$TiSi_{2.3}$/In_2O_3/Al sample.

Within the resolution and sensitivity of this analytical method, there is no detectable interdiffusion or layer formation at the interfaces of the annealed sample.

This result is confirmed by measurements of the dc current-voltage characteristics of a shallow n^+-p junction with the ⟨Si⟩/In_2O_3/Al contact scheme. Figure 2(a) shows the reverse leakage current (measured at -1 V) as a function of annealing temperature. The leakage current remains almost unchanged after annealing the diodes at 600 °C for 30 min. Only a slight increase in leakage current from 150 to about 250 pF is observed after annealing the diodes at 650 °C for 30 min. All diodes annealed at 700 °C are shorted and have clearly degraded surface morphology. On the other hand, diodes with a Si/Al metallization, e.g., without a diffusion barrier, were all shorted already after annealing the sample at 500 °C for 30 min. This result shows that the presence of the In_2O_3 layer enhances significantly the thermal stability of the Si/Al contacts.

A contacting layer is usually added between a semiconductor and a diffusion barrier to satisfy the electrical requirements of devices.[3] In our study a ⟨Si⟩/$TiSi_{2.3}$/In_2O_3/Al metallization was tested using n^+-p silicon shallow junctions. Figure 2(b) shows the reverse leakage current of diodes with the ⟨Si⟩/$TiSi_{2.3}$/Al and ⟨Si⟩/$TiSi_{2.3}$/In_2O_3/Al metallizations as a function of the temperature for 30 min annealing. We find that the ⟨Si⟩/$TiSi_{2.3}$/Al contact is stable up to 500 °C. The ⟨Si⟩/$TiSi_{2.3}$/In_2O_3/Al contact begins to show signs of electrical deterioriation after 600 °C heat treatment; the leakage current increases from 100 to 600 pF. Diodes annealed at 650 °C are shorted.

It is interesting to note that the ⟨Si⟩/In_2O_3/Al metallization system is more stable than the ⟨Si⟩/$TiSi_{2.3}$/In_2O_3Al system. Similar results were observed in Si/TiN/W versus Si/$TiSi_2$/TiN/W metallization by Suguro *et al.*[15] The Si/TiN/W metallization was stable up to 950 °C for 6 h, but the formation of WSi_2 was observed after annealing the Si/$TiSi_2$/TiN/W at 950 °C for 30 min. A proven explanation for this effect does not exist yet.

The present results clearly establish that In_2O_3 can act as an effective diffusion barrier between Al and Si beyond the eutectic temperature of the Al-Si (577 °C). A study of the interfacial reactions between the In_2O_3 barrier layer and Al or Si is under way.

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