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OPTICAL PROCESSING FOR SEMICONDUCTOR DEVICE FABRICATION

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ABSTRACT

A new technique for semiconductor device processing is described that uses optical energy to produce local heating/melting in the vicinity of a preselected interface of the device. This process, called Optical Processing, invokes assistance of photons to enhance interface reactions such as diffusion and melting, as compared to the use of thermal heating alone. Optical processing is performed in a "cold wall" furnace, and requires considerably lower energies than furnace or rapid thermal annealing. This technique can produce some device structures with unique properties that cannot be produced by conventional thermal processing. Some applications of Optical Processing involving semiconductor-metal interfaces are described.

INTRODUCTION

Fabrication of electronic devices requires process steps such as diffusion, oxidation, and contact formation. During these process steps the desired reactions take place only at the interfaces. For example, in a junction formation process the dopant diffusion may take place only a fraction of a micron deep; likewise, oxides are typically grown less than 1000Å thick (1-3) Even though the reactions are primarily limited to interfaces, the conventional approach for carrying out various device fabrication process steps involves heating the entire wafer in a furnace to the process temperature. A recent method, rapid thermal annealing (RTA), also heats the entire wafer nearly isothermally; however, due to the use of optical heating, the rate-of-increase in the temperature can be very rapid (4). Thus, in spite of the fact that the device fabrication often requires reaction(s) to take place only near the surface or interfaces, the methods developed todate require that the entire wafer be heated. Any attempts to locally heat the material by producing large steady-state temperature gradients can generate large stresses and, hence, produce defects in the material or even shatter the process wafers. The only somewhat successful approach for local heating consists of heating by means of very short pulses from a short wavelength laser. Even with laser heating, only the front surface can be locally heated. Due to many disadvantages such as low throughput, long coherence length of the laser light, and high cost of laser processing, this technology is still in the research mode.

This paper describes a new processing technique that can preferentially deliver energy to an interface of a semiconductor (S) and a metal (M), even if the interface is deep inside the material. The energy delivered to the interface can be controlled to modify the interface characteristics. The major emphasis of this paper is to describe some applications of this processing technique for formation of low-resistivity ohmic contacts on semiconductors with some unique properties.

OPTICAL PROCESSING

In Optical Processing, the S-M interface is illuminated from the semiconductor side with a spectrum such that the major part of the light reaches the interface. The incident light produces local heating, accompanied by enhanced diffusion and/or melting, in the vicinity of the interface. The thickness of the melt or the diffusion depth can be controlled by controlling the energy delivered to the device. The local melt can be generated to form an alloyed region that regrows epitaxially on the silicon substrate and produces an ohmic contact of extremely low contact resistivity. The energy delivered to the device can also produce bulk heating to induce other predetermined thermal effects. The interface reaction is strongly diminished if the S-M interface is not directly illuminated.

Optical Processing and Rapid Thermal Annealing (RTA) differ in the basic mechanisms involved in each process . In Optical Processing the reaction at the interface is assisted by photons. Hence, the reaction occurs predominantly at the illuminated interface; the same reaction is greatly slowed if the interface is masked. In contrast, a typical RTA is a thermal process that cannot discriminate between the front and the backside of the device since such a process is completely thermally controlled [4].

Optical Processing can be best understood by an example of its application. Here we will consider an example of simultaneous formation of ohmic contacts to a silicon solar cell.

FABRICATION OF CONTACTS ON SOLAR CELLS

Fabrication of low-resistance metal contacts on solar cells requires sintering and alloying of the S-M interfaces to produce the desired ohmic characteristics. In the fabrication of a typical n+/p solar cell, the back metal must by alloyed to have a low-resistivity contact on the higher-resistivity base region, while the front contact must be only mildly sintered to prevent metal from punching through the highly doped emitter, and the depletion regions. The need for different processing conditions for the front and back contacts necessitates several process steps, the number depending on the method of metal deposition (e.g., plating, screen printing, or evaporation). As an example, Table 1 shows the typical steps involved in a conventional process using evaporated aluminum to make contacts on both sides. Also indicated in the table are the process steps for making the contacts by optical processing, as discussed below.

Table I: Comparison of process steps for fabricating contacts to solar cells using conventional methods and Optical Processing (this example uses Al on both sides).

	FURNACE ANNEAL OR RTA	OPTICAL PROCESSING
1	Deposit Al on back side	Deposit Al on front and back
2	First alloy	Sinter/alloy
3	Strip excess Al in HCl then Rinse in DI water; dry	
4	Dil. HF dip (or fume)	
5	Deposit Al on front	
6	Sinter front Al	
7	Deposit additional Al on back	

Figure 1 illustrates the structure of an n+/p solar cell which has a thin layer of Al deposited on the entire backside and narrow Al pads on the front side. In order to produce high quality contacts to the cell, the back contact must be alloyed without alloying the front. To accomplish this, the cell is placed in an Optical Processing Furnace (OPF) with the junction side upward, as shown schematically in Figure 2. The OPF consists of a quartz muffle that is illuminated from above by quartz-halogen lamps. The optics of the light sources are designed so that the illumination in the process zone is highly uniform. Process gases such as Ar, N_2, and O_2 are regulated to flow through the furnace. The walls of the muffle are maintained "cold" by flowing N_2 along the outside walls of the muffle. The spectrum, intensity, and duration of the incident flux are chosen for the specific application. Figure 3 shows typical process cycles using Al contacts for silicon solar cells with and without antireflection coating. As seen from this figure, the process is controlled in terms of the optical power delivered to the device.

RESULTS

Figure 4 schematically illustrates the effects of Optical Processing cycles, described in Figure 3, on the front and back interfaces of a solar cell. While the front contact does not show the presence of an alloyed region, the back contact forms a thin Si-Al alloyed region adjacent to the Si surface. Figure 5 is a high resolution cross-sectional TEM image of the Si/Si-Al alloy interface showing an epitaxial growth of the alloy. By controlling the light intensity, and the process time, one can control the thickness of the alloyed back layer and the sinter conditions for the front contact simultaneously. In order to compare the degree of reaction at the front and the back side of the cell we have processed some devices under accentuated conditions. Figures 6 and 7 show the Al and Si profiles of these "strongly" processed contacts before and after removal of the residual Al. Figures 6a and 6b show that the back contact has melted to produce an alloyed interface region of about 0.4 μm. However, Figures 7a and 7b show that the front contact has an alloyed region of << 0.1 μm. It is important to point out that under normal process conditions the alloyed interface thicknesses are considerably smaller than those in Figures 6 and 7.

The quality of the contacts formed by Optical Processing is extremely high. From the initial measurements of contacts fabricated on 0.5-10 Ω-cm substrates, we have estimated the contact resistivity to be less that 10^{-4} Ω-cm^2, up to current densities of 2 A/cm^2. As a result, solar cell contacts made by Optical Processing have excellent characteristics. Figure 8 shows the I-V characteristic of a large-area 32 cm^2 cell with contacts produced by this technique. The efficiency of the cell is slightly above that for the same cell with contacts made with conventional process steps. Optical Processing has also been applied to already fabricated contacts on fully finished commercial cells resulting in the improvements in the cell performance.

Although we have only discussed formation of Si-Al contacts, the same principle is applicable to many other semiconductor-metals combinations. We have used other metals, such as Cu, Ni, and Pd, in various combinations with silicon and obtained excellent results.

SPECIAL PROPERTIES OF METAL CONTACTS FORMED BY OPTICAL PROCESSING

The above described results involving controlled melt and diffusion at a semiconductor interface permits fabrication of some unique structures. Here we describe examples of two regimes of Optical Processing to control the S-M interface properties - the melt regime, and the diffusion regime. In the melt regime the interface is provided with sufficient energy to create a uniform melt that spreads laterally over the entire S-M interface. When the source of energy is removed, the melted region regrows epitaxially over the substrates. In the diffusion regime, the energy dissipated at the interface cannot produce a melt; however, localized regions of the enhanced diffusion across the interface can take place forming low-energy sites of nucleation. For example, enhanced diffusion at a Si-Al interface can create transport of Si to define etch pits bounded by (111) planes. These mechanisms can be used to produce following characteristics of the devices.

A. High reflectance ohmic contacts:

Typically low-resistivity ohmic contacts, produced by the conventional processing, result in graded interfaces that allow light to be transmitted from semiconductor into the metal where it can be absorbed. Optical processing allows the interface to be made abrupt by confining the melt to less than 100 Å. Such an interface can reflect light very effectively, and yet have an excellent ohmic characteristics with low resistivity. Figure 9 shows reflectivity of an optically processed contact as measured from the silicon side and from the aluminum side. The reflectivity from silicon side, at wavelengths larger than the 1.1 μm, is about 80%;

corresponding reflectivity for a conventionally processed contact is typically less than 50%. This figure also shows that aluminum remains highly reflective after optical processing.

B. Dry texturing:
Optical Processing of a contact in the diffusion regime (followed by a second process step involving melt regime) produces dry texturing of the interface with a highly reflecting ohmic contact. Such a contact can efficiently scatter light to produce light trapping useful for thin-film solar cells. Figures 10A, 10B, and 10C are the photographs of the texture, produced under different process conditions, showing the control of the texture size and the density. Figure 10D is a higher magnification photograph showing pyramid shape of the texture formed on a (100) silicon wafer.

ADVANTAGES OF OPTICAL PROCESSING

Advantages of Optical Processing over conventional processes include

- Because heating/melting initiates at the interface (and can be confined to a thin region at the interface), the effect of the impurities in the ambient gas(es) on the characteristics of the contact is minimal compared to either furnace processing or Rapid Thermal Annealing (RTA). In Optical Processing the surfaces of the Al contacts typically remain shiny and do not require further preparation for additional metallization, such as solder dip (see Figure 9);
- Optical Processing is a "cold wall" process which minimizes the impurity out-diffusion as well as permeation from furnace walls;
- The process results in large-area uniformity of the alloyed/sintered layers. This feature is evidenced by the fact that the Si-Al contacts produced are free from the "spikes" and pitting produced by other processes;
- The process requires much less power than furnace or RTA anneals;
- The process is rapid, has high throughput, and can make devices with unique characteristics;
- The process requires fewer steps than conventional approaches and results in significant cost savings;
- Optical Processing allows control of dimensions both in depth and laterally. This is due, in part, to the fact that interactions can be induced to occur at considerably lower temperatures. This feature is important for VLSI and ULSI applications;
- This technique lends itself to multi-layer contact formation.

Optical Processing appears to have a strong commercial potential. This processing technique has already developed strong interest in the photovoltaic industry for commercial applications. This technology is also expected to have major applications in microelectronic device fabrication.

ACKNOWLEDGEMENT

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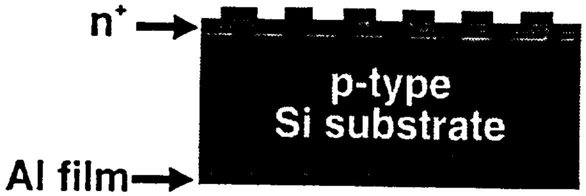

Figure 1. Schematic of the solar cell configuration used for simultaneous contact formation by Optical Processing

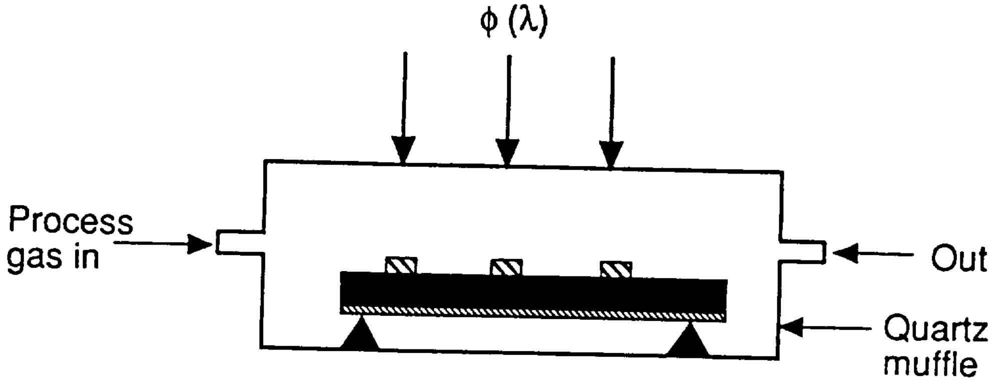

Figure 2. Illustration of the use Optical Processing for the simultaneous formation of front and back contacts

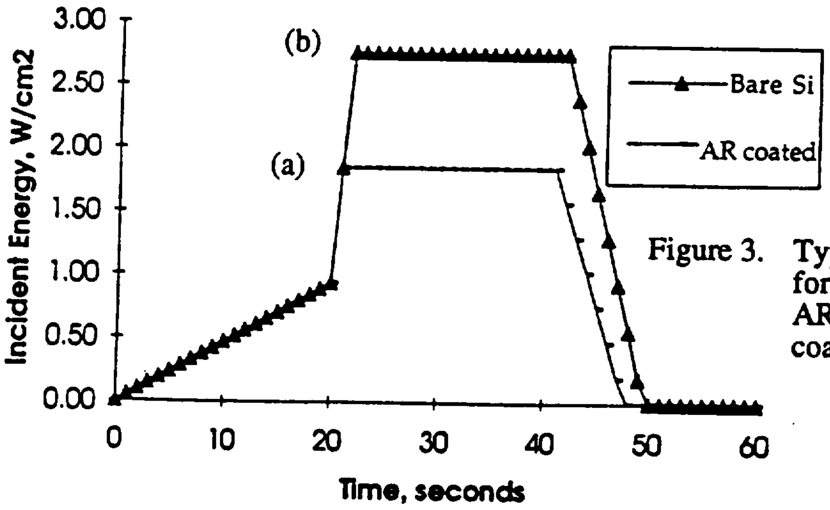

Figure 3. Typical process cycles for forming Si-Al contacts: (a) with AR coating; (b) without AR coating

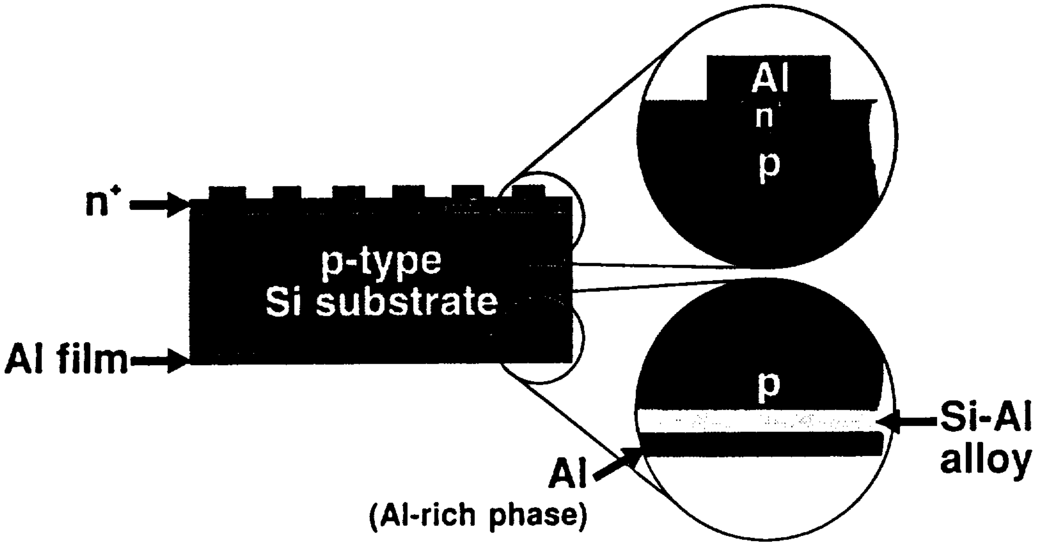

Figure 4. Illustration of the interface structure produced by Optical Processing

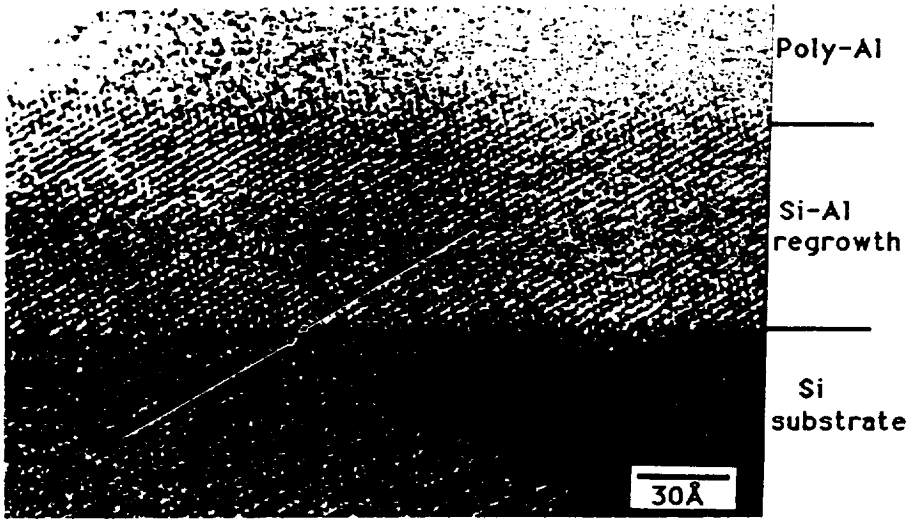

Figure 5. High resolution XTEM image of the Si/Si-Al alloy, showing epitaxial growth of the alloy on the substrate

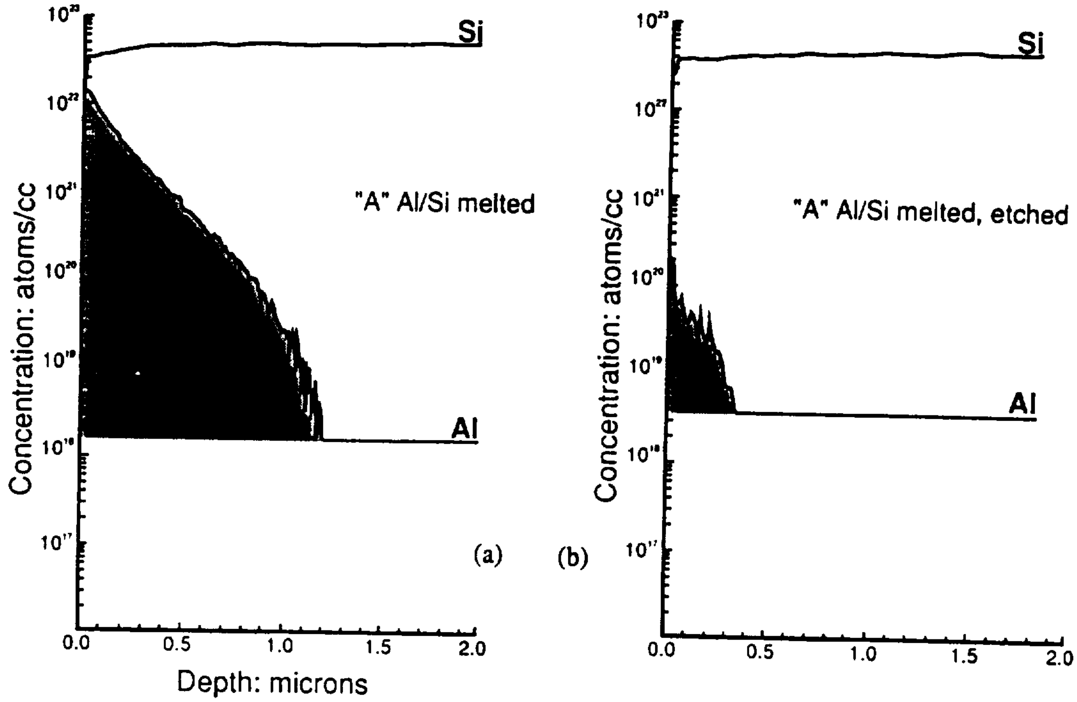

Figure 6. SIMS profiles of Al and Si on the backside contact of a "strongly" processed sample: (a) as-formed; (b) after residual Al was etched

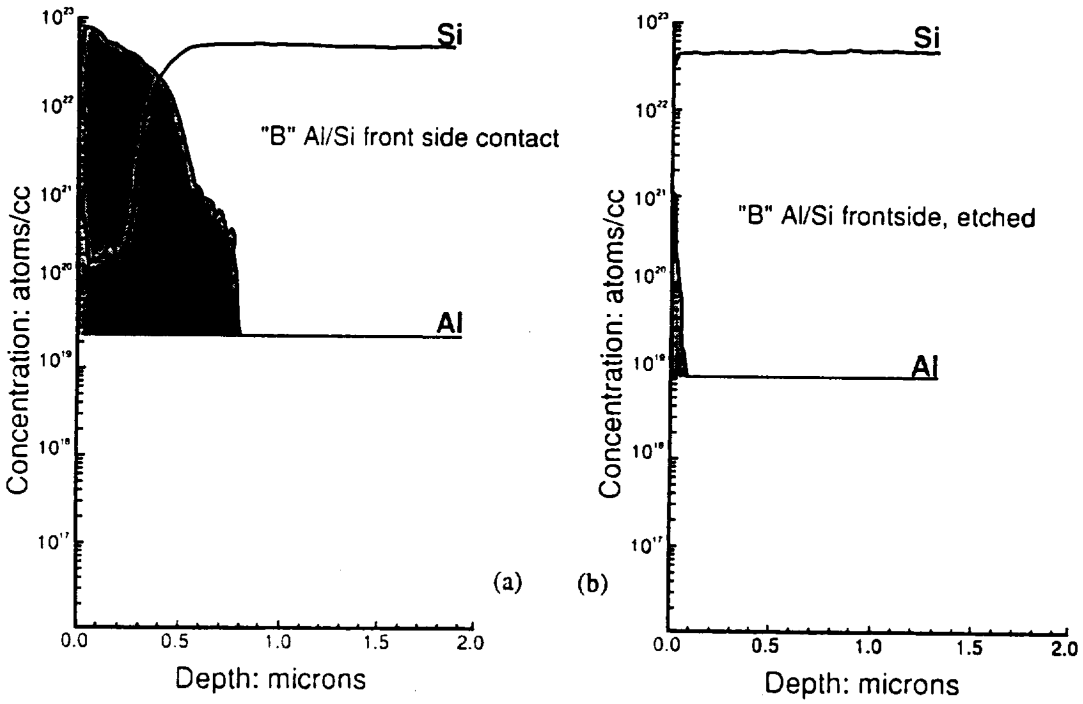

Figure 7. SIMS profiles of Al and Si on the front contact of a "strongly" processed sample: (a) as-formed; (b) after residual Al was etched

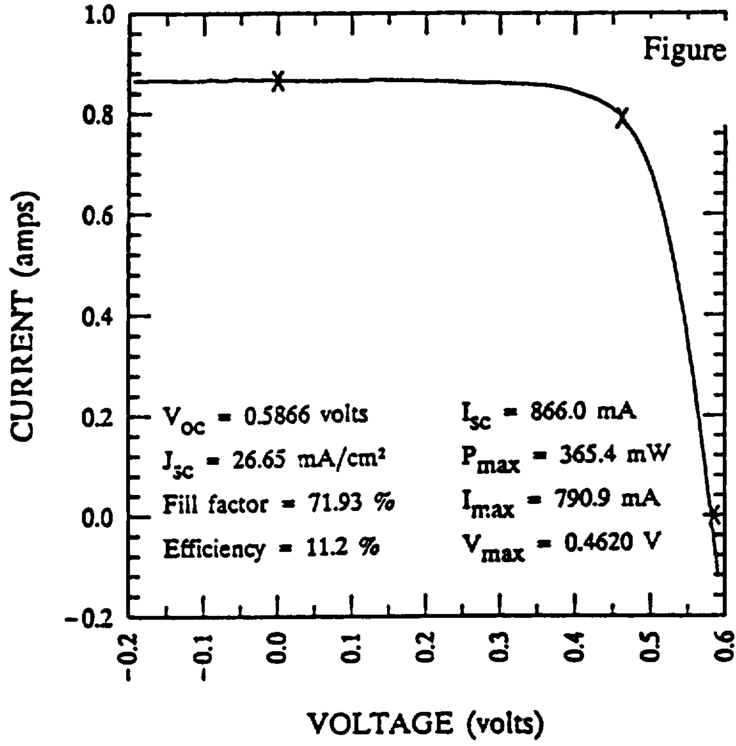

Figure 8. I-V characteristic of a 32.5 cm cell with contacts formed by Optical Processing

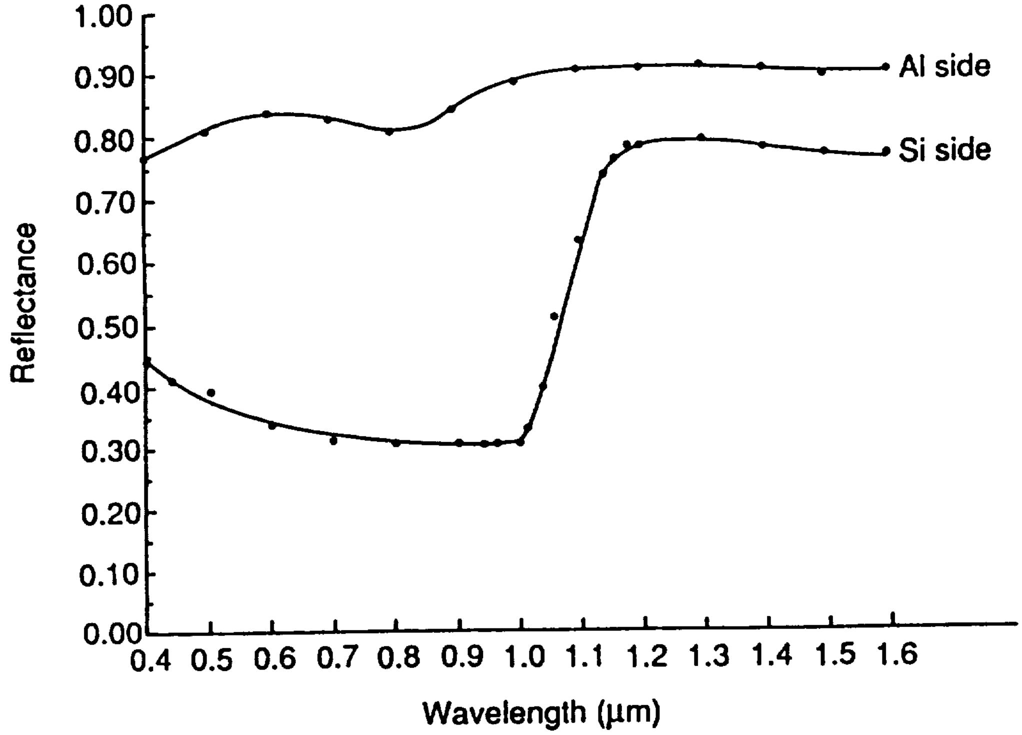

Figure 9. Reflectance plot of a high-reflectivity contact (a) from silicon side, (b) from Al side

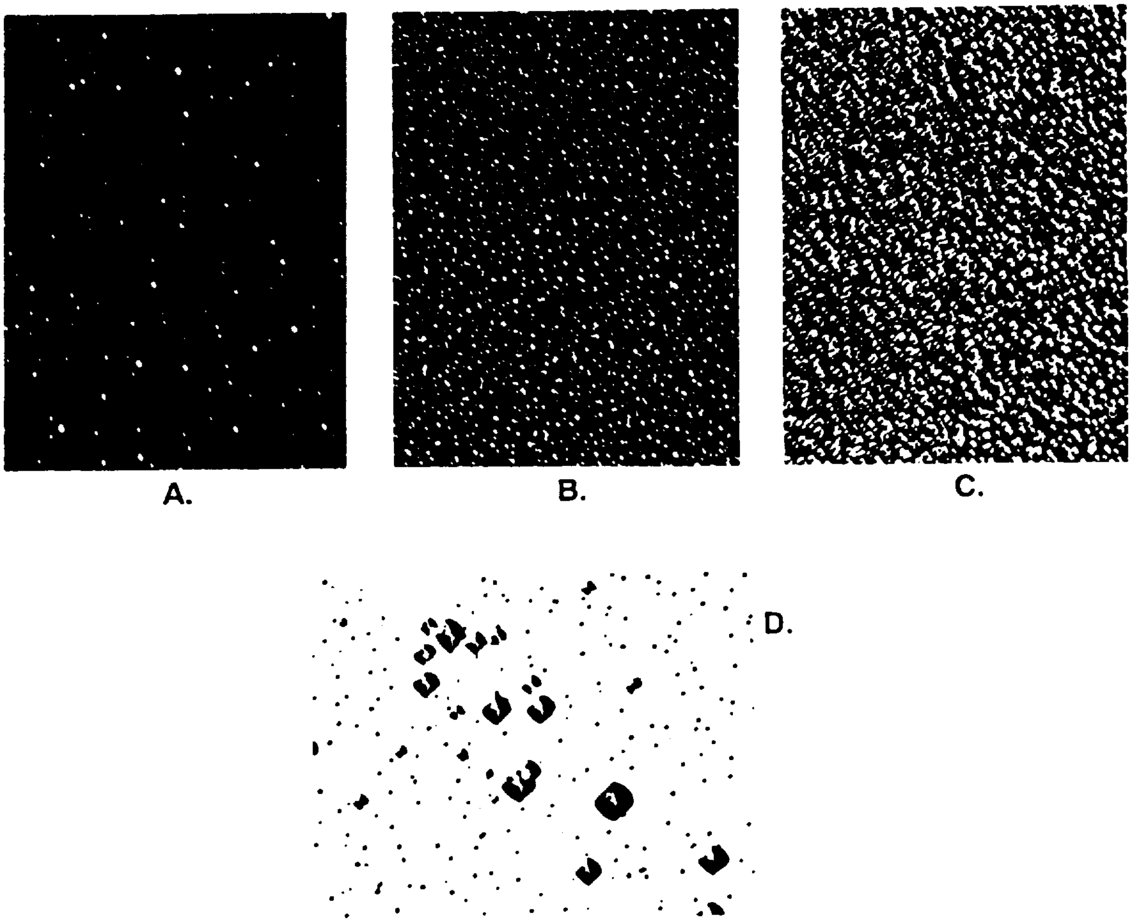

Figure 10. Photographs showing variation in the texture density and size due to different Optical Processing conditions (see text)

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A SCANNING DEFECT MAPPING SYSTEM FOR SEMICONDUCTOR CHARACTERIZATION

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ABSTRACT

We have developed an optical scanning system that generates maps of the spatial distributions of defects in single and polycrystalline silicon wafers. This instrument, called Scanning Defect Mapping System, utilizes differences in the scattering characteristics of dislocation etch pits and grain boundaries from a defect-etched sample to identify, and count them. This system simultaneously operates in the dislocation mode and the grain boundary (GB) mode. In the "dislocation mode," the optical scattering from the etch pits is used to statistically count dislocations, while ignoring the GB's. Likewise, in the "grain boundary mode" the system only recognizes the local scattering from the GB's to generate grain boundary distributions. The information generated by this instrument is valuable for material quality control, identifying mechanisms of defect generation and the nature of thermal stresses during the crystal growth, and the solar cell process design.

INTRODUCTION

Crystal defects such as dislocations and grain boundaries strongly influence the performance of all electronic devices. The influence of defects is particularly important for solar cells because the commercial silicon solar cells are fabricated on low-quality material that contains high densities of defects and impurities. In the large-grain polycrystalline silicon substrates, used for commercial solar cells, the dominant defect appears to be the intragrain dislocations. A knowledge of the distribution of defects is necessary for the following reasons: (i) the distribution of defects reflects the nature of thermal stresses generated during the crystal growth. It is known that dislocation formation can take place when the magnitude of thermal stresses during the crystal growth exceeds the yield stress, (ii) the degree of degradation in the device performance due to defects depends on their distribution as well as their density. This is because the localized regions of high dislocation density can produce a significantly higher effect on the cell performance compared to a case if the dislocations were uniformly distributed over the cell area, (iii) a knowledge of the defect distribution can allow a better design of the cell and the cell fabrication processes, (iv) determination of the variations in the defect distributions from wafer-to-wafer, and from ingot-to-ingot are essential for material quality control.

The two methods commonly used for determining the dislocation density in semiconductor materials are: X-ray topography and chemical etching. X-ray topography is typically only used for single crystal wafers of low dislocation density. The most commonly used method consists of etching the material in a chemical solution that produces etch pits at the dislocation sites. Subsequently, the etch pits are counted under an optical microscope. This procedure can be extremely tedious and time-consuming for large-area wafers (even with the help of image analysis attachments for the optical microscope). A similar procedure can be applied to polycrystalline silicon substrates. However, care must be exercised in selecting the suitable etches, because many of the etches do not work well for polycrystalline substrates. For example Wright and Dash etches produce etch pits of different shapes and sizes for different orientations (1, 2). A unique etch, known as "Sopori etch," was formulated for polycrystalline silicon to produce etch pits of the same size on all orientations (3). This isotropic etch consists of