~~SAN-1284-8-2~~

DOE/SF/01284--T5

GALLIUM ARSENIDE THIN FILMS ON TUNGSTEN/GRAPHITE SUBSTRATES: PHASE II

SEE LETTER DTD MARCH 20, 1978

Quarterly Project Report No. 2

For Period December 1, 1977 to February 28, 1978

MASTER

Prepared under DOE Contract ~~EY-76-C-03-1284~~ AC03-76SF01284

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March, 1978

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Summary

This is the Second Quarterly Project Report of the Phase II of a research program "Gallium Arsenide Thin Films on Tungsten/Graphite Substrates" supported by the U. S. Department of Energy under Contract No. EY-76-C-03-1284. The objectives of this contract are to investigate thin films of gallium arsenide on tungsten/graphite substrates and to prepare solar cells with an AM1 efficiency of 6% or higher by August 1978.

Efforts during this quarter have been directed to (1) the deposition and characterization of gallium arsenide films on tungsten/graphite substrates by the arsenic and arsine processes, (2) the construction and operation of an apparatus for the deposition of titanium dioxide films, and (3) the fabrication and evaluation of MOS solar cells on tungsten/graphite substrates.

Gallium arsenide films have been deposited on tungsten/graphite substrates by the reaction of gallium, hydrogen chloride, and arsenic in a hydrogen flow. The structural and electrical properties of these films are very similar to those obtained by the arsine process. The initial stage of the deposition of gallium arsenide films on tungsten/graphite substrates has been investigated by the scanning electron microscopy.

An apparatus for the low temperature deposition of titanium dioxide films by the hydrolysis of tetraisopropyl titanate in an argon atmosphere has been constructed. Titanium dioxide films of 600-700 Å thickness have been deposited on thin film gallium arsenide solar cells at about 100°C as antireflection coatings.

The fabrication and characterization of thin film gallium arsenide MOS solar cells have been continued. The best cells at present have AM1 efficiencies of higher than 6%, and the titanium dioxide coated solar cells exhibit no electrical instabilities. The barrier height and spectral response of the cell have been measured.

I. Introduction

This is the Second Quarterly Project Report of the Phase II of a research program "Gallium Arsenide Thin Films on Tungsten/Graphite Substrates" supported by the Division of Solar Technology of the U. S. Department of Energy under Contract No. EY-76-C-03-1284. The objectives of this contract are to perform intensive studies concerning thin films of gallium arsenide on tungsten/graphite substrates and to prepare reproducibly thin film gallium arsenide solar cells with an AM1 efficiency of 6% or higher by August 1978.

The principal approach used in this program is the deposition of gallium arsenide films on low-cost foreign substrates by the reaction of gallium, hydrogen chloride, and arsine in a hydrogen atmosphere in a gas flow system. During the first phase of this program, tungsten-coated graphite and germanium films recrystallized on tungsten/graphite were used extensively as substrates for the deposition of gallium arsenide films.(1) Epitaxial gallium arsenide films were deposited on recrystallized germanium films which contained elongated grains of up to several millimeters in length.(2) However, these films have high electron concentrations, $2 \times 10^{17} cm^{-3}$ and higher, due to the auto-doping effect associated with the halide process and the high diffusion rate of germanium along grain boundaries in gallium arsenide films. Consequently, MOS type solar cells prepared from these gallium arsenide films show excessive dark current in the forward direction, resulting in low photocurrent, open-current voltage, and fill factor. Therefore, the use of recrystallized germanium films as a substrate for the deposition of gallium arsenide films has been de-emphasized.

Gallium arsenide films deposited on tungsten/graphite substrates are essentially polycrystalline with average crystallite size of about 10 μm. In spite of the relatively small crystallites, MOS type solar cells have AM1 efficiencies of higher than 5%. The use of tungsten/graphite substrates has been further emphasized in the second phase of this program. In addition, the use of graphite substrates has also been under investigation. The use of a heavily-doped interfacial layer could reduce the interface resistance to a tolerable level.

The reaction between gallium, hydrogen chloride, and arsine in a hydrogen flow has been used for the deposition of gallium arsenide films since the early stage of this program. However, the carrier concentration in deposited films was found to vary with the source of arsine due presumably to variations in impurity contents in commercial arsine. During this reporting period, the reaction between gallium, hydrogen chloride, and arsenic has been investigated for the deposition of gallium arsenide films since high purity arsenic is readily available. In addition, an apparatus for the deposition of titanium dioxide films has been constructed and used for the deposition of antireflection coatings on gallium arsenide solar cells. Also, the fabrication and characterization of thin film gallium arsenide solar cells on tungsten/graphite substrates have been continued. The results to date are discussed in the following sections.

II. Deposition of Gallium Arsenide Films by the Gallium-Hydrogen Chloride-Arsenic Process

Gallium arsenide films used in this program have been deposited by the reaction between gallium, hydrogen chloride, and arsine because of its simplicity and low cost. However, the impurity content in commercial arsine often varies, thus affecting the carrier concentration in deposited gallium arsenide films. To minimize these variations, the reaction between gallium, hydrogen chloride, and arsenic has been investigated for the deposition of gallium arsenide films since arsenic is readily available in purities of higher than 99.999%. The gallium-hydrogen chloride-arsenic process has been reported by others.(3) In this process, hydrogen chloride is used to convert gallium into gallium monochloride, and hydrogen is used as a carrier gas for arsenic. The reaction between gallium monochloride and arsenic on the substrate surface yields gallium arsenide according to the reaction

$$6\ \mathrm{GaC\ell(g)} + \mathrm{As_4(g)} \rightarrow 4\mathrm{GaAs(s)} + 2\mathrm{GaC\ell_3(g)}.$$

Single crystalline gallium arsenide wafers with main faces of a {100} orientation were used as substrates for this deposition process. In these experiments, a five zone furnace is used to maintain the temperatures of the substrates and gallium at 730-750°C and 870-890°C, respectively. The temperature of arsenic was adjusted to yield an As/Ga molar ratio of 2. The flow rate of hydrogen chloride was varied in the range of 10-45 mℓ/min and the flow rate of hydrogen was 1 ℓ/min. N-type epitaxial films of good structural perfection were obtained in all cases. The net carrier concentrations in gallium arsenide films are in the range of $(4\text{-}8) \times 10^{15}\mathrm{cm}^{-3}$. Homoepitaxial gallium arsenide films were also prepared by using arsine recently procured from a different supplier, and the concentration in deposited gallium arsenide films are in the range of (1-4) x $10^{16}cm^{-3}$.

Tungsten coated graphite substrates were also used for the deposition of gallium arsenide films by the reaction between gallium, hydrogen chloride, and arsenic. Using hydrogen and hydrogen chloride at flow rates of 1 ℓ/min and 30 mℓ/min, respectively, and the arsenic temperature of 590°C, the deposition rate of gallium arsenide was about 0.8-1 μm/min, and the average crystallite size was 10-15 μm. The structural and electrical properties of deposited films are very similar to those of gallium arsenide films deposited from the recently procured arsine. The deposition of gallium arsenide films by the reaction between gallium, hydrogen chloride, and arsenic has been shown to be a promising method; however, the arsine process will continuously be used in this program because of its simplicity.

III. Deposition of Titanium Dioxide Films as AR Coatings

III.1 Introduction

The antireflective coating is an important parameter in the design and fabrication of solar cells.(4,5) Since gallium arsenide has relatively high refractive indices, about 3.6 at 900 nm and 4.8 at 450 nm at room temperature, more than 30% of the incident light is lost by reflection, and coatings of appropriate refractive index and thickness must be applied to reduce this loss. The optical thickness of the coating should be one-quarter wavelength at wavelength near the peak of the cell response-solar output product curve. The optimum refractive index of the coating to give zero reflectance at the quarter-wavelength thickness is $(n_1\ n_2)^{\frac{1}{2}}$, where n_1 and n_2 are the refractive indices of the semiconductor and the medium surrounding the antireflection coating, respectively. Thus, the optimum refractive index of coatings should be about 2 for uncovered cells and about 2.5 for cells with glass covers (refractive index 1.5). In practice, the refractive indices of both the semiconductor and the antireflecting coatings are dispersive; however, the choice of a refractive index for the antireflection coating close to the value given by $(n_1\ n_2)^{\frac{1}{2}}$ ensures minimum overall reflectance.

In the case of Schottky barrier and MIS type solar cells, the selection of antireflection coatings are especially important since the metal films on the semiconductor surface greatly increases the solar reflectance. For example, for 100 Å metal films on silicon or gallium arsenide, reflection is the biggest optical loss, amounting to about 35% for the most transparent films such as copper, gold, or silver.(6) A method for obtaining parameters of practical antireflection coatings for Schottky barrier solar cells has been developed utilizing the measured equivalent index of refraction obtained from ellipsometry.(7) Gallium arsenide Schottky barrier solar cells require an antireflection coating with a refractive index of about 2.35 when matching to air at 600 nm, and higher indices are required if matching to an adhesive or encapsulant material is desired.

Tantalum oxide and niobium oxide films with refractive indices of 2.2-2.4 have been developed as antireflecting coatings for silicon solar cells.(8) Although the refractive indices of these oxides are nearly ideal as antireflection coatings for thin film gallium arsenide MIS solar cells, the application of these films requires relatively high substrate temperature, about 500°C, resulting in the degradation of the electrical properties of MIS structures. Recently, Hovel has reported the use of the hydrolysis of tetraisopropyl titanate by a spray process in air for the deposition of titanium oxide films on gallium arsenide p-n junction and Schottky barrier solar cells at relatively low temperatures, 50° or above.(9) The deposition rate was 5-10 Å/sec, and the films deposited at temperatures below 200°C were found to be amorphous. The refractive index increases linearly with deposition temperature from 1.9 at 50°C to 2.4 at 300°C; the absorption edge increases from 3400 Å for the low temperature films to 4000 Å for films deposited at 400°C. These results indicate that titanium dioxide is an attractive antireflection-coating material for thin film gallium arsenide solar cells, and this approach has been selected in this work.

III.2 Deposition of Titanium Dioxide Films

Titanium dioxide, because of its high dielectric constant (rutile has a dielectric constant of 90 ⊥ to the c-axis and 180 parallel to the c-axis), has been studied by many investigators. Several techniques, including vacuum evaporation, sputtering, oxidation of evaporated titanium films, and chemical vapor deposition have been used for the preparation of titanium dioxide. However, its properties vary widely with the preparation technique due presumably to the non-stoichiometry and different crystallinity in the deposit.

Chemical vapor deposition is considered as the most versatile technique for the deposition of titanium dioxide.(10) The chemical reactions used for the deposition of titanium dioxide include the hydrolysis and oxidation of titanium tetrachloride, the pyrolysis and hydrolysis of titanium alkoxide compounds, etc. For example, the oxidation of titanium tetrachloride in an oxygen atmosphere at 990°-1100°K yields essentially the rutile modification,(11) and titanium alkoxides (such as tetraisopropyl titanate) with titanium-oxygen bonds decompose at 350° or above to yield titanium dioxide.(12) However, the temperatures required in these reactions are excessive for gallium arsenide Schottky barriers. On the other hand, titanium tetrachloride and tetraisopropyl titanate hydrolyze readily, but the experimental conditions must be carefully controlled to yield adherent films on substrates. In a German process, the object heated at 200°C was rotated in front of an oscillating burner which was fed with a central jet of titanium tetrachloride vapor carried in dry air. Surrounding this jet and separating it by an annular jet of dry air, was a peripheral jet of moist air. Mixing of the various gas streams occurred at the sample surface, hydrolyzing the titanium tetrachloride and depositing a thin film of titanium oxide on the object. A similar arrangement has been used for depositions of titanium dioxide films on germanium, steel, and other metals.(14)

When titanium dioxide is used as an antireflecting coating for solar cells, the deposition conditions must be carefully controlled to minimize the formation of interface states and other defects. One important requirement for the chemical vapor deposition of dielectric films is that the reaction should be predominately heterogeneous taking place on the substrate surface. Otherwise, reactions in the volume surrounding the substrate can yield solid products in the gas phase, and the deposition of these solids on the substrate would yield nonadherent material. The volume reaction can be suppressed by using a low partial pressure of the reactants in the reaction chamber and a high linear velocity of the gas mixture over the substrate surface. This requirement is extremely important in the deposition of adherent titanium dioxide films since the hydrolysis of titanium tetrachloride or tetraisopropyl titanate takes place readily at room temperature.

Since water vapor is used in the deposition of titanium dioxide films, and water vapor could cause undesirable contaminations in the existing CVD apparatus for tungsten, silicon nitride, and others, an apparatus was constructed for the exclusive deposition of titanium dioxide films. It consists of two parts: the gas flow control and the reaction tube. A schematic diagram of the apparatus is shown in Figure 1.

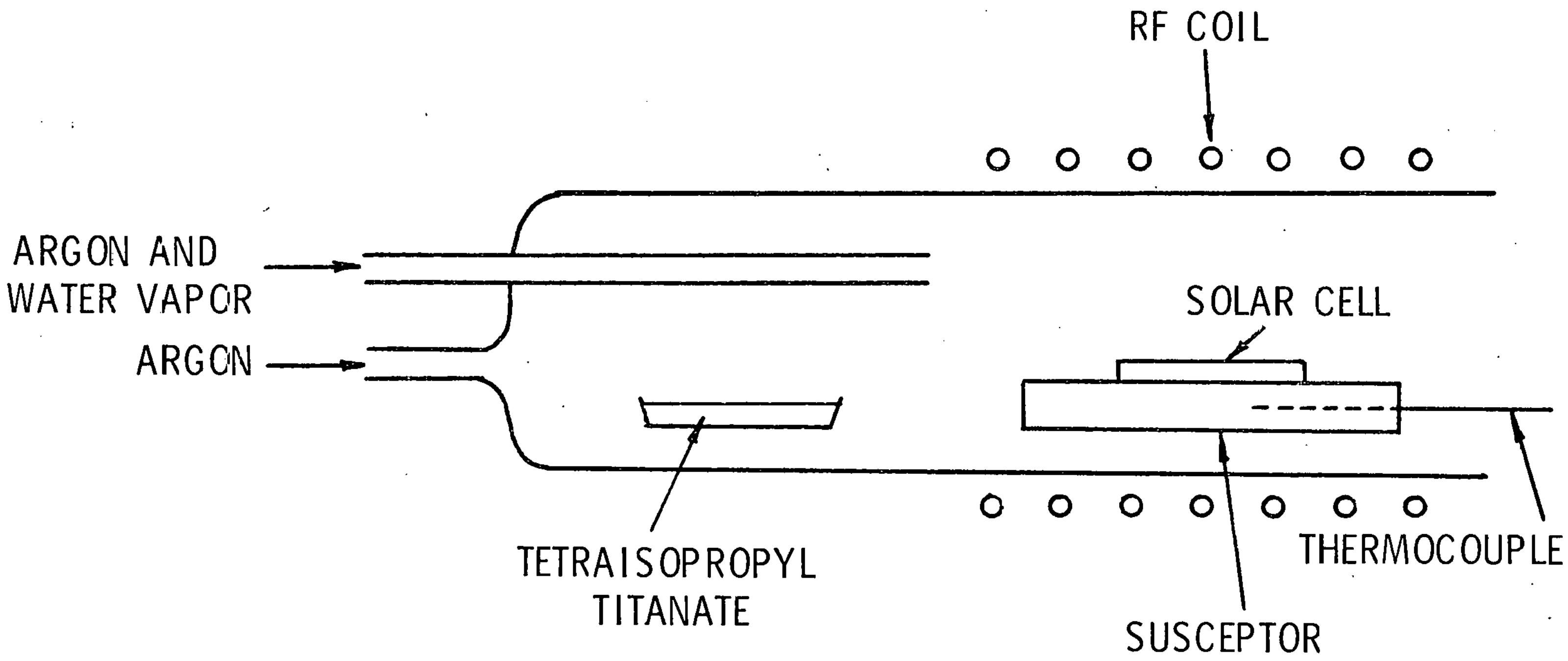

Figure 1 Schematic diagram of the apparatus for the deposition of titanium dioxide films.

The solar cells are supported on a graphite susceptor in a fused silica reaction tube. The susceptor is heated externally by an rf generator, and its temperature is monitored by a thermocouple inserted into the susceptor. The tetraisopropyl titanate container is also placed in the reaction tube and its vapor is carried over to the substrate surface by argon. Argon is also used as a carrier gas to introduce water vapor to the substrate surface. It is important that the mixing of tetraisopropyl titanate and water vapor take place on the surface of the substrate to minimize homogeneous nucleations.

A number of experiments have been carried out using argon flow rate in the range of 2-10 ℓ/min, solar cell temperature at 60-100°C, and sufficient tetraisopropyl titanate and water vapor to yield deposition rates of 50 Å - 500 Å/min. The deposited film is not yet uniform at present, and further optimization is underway.

IV. Gallium Arsenide Films on Tungsten/Graphite Substrates

Investigations of gallium arsenide films on tungsten/graphite substrates have been continued with emphasis on the initial nucleation during the deposition of gallium arsenide and the fabrication and characterization of MOS solar cells.

IV.1. Deposition of Gallium Arsenide Films

Gallium arsenide films have been deposited on tungsten/graphite substrates by the reaction of gallium, hydrogen chloride, and arsine in a fused silica reaction tube of 55 mm ID; the tungsten film, approximately 3-5 μm in thickness, was deposited by the thermal reduction of tungsten hexafluoride at 500°C. In most experiments carried out during the first phase of this work, the temperature of gallium was maintained at 880-890°C, and the flow rates of hydrogen, hydrogen chloride, and arsine were fixed at 1 ℓ/min, 45 mℓ/min, and 90 mℓ/min, respectively. The deposition rate and average crystallite size have been found to depend strongly on the substrate temperature. In films deposited at 775°C, the deposition rate is approximately 1.5 μm/min, and the average crystallite size is larger that 10 μm. The carrier concentrations are usually in the range of $5 \times 10^{16} - 10^{17}$ cm^{-3}.

The effects of the concentration of hydrogen chloride in the reactant mixture have been studied using hydrogen, hydrogen chloride, and arsine at flow rates of 1 ℓ/min, 15 mℓ/min, and 30 mℓ/min, respectively. At a substrate temperature of 775°C, the average deposition rate is about 0.6 μm/min, and the average crystallite size is 4-5 μm in films of 15 μm thickness. The crystallographic properties of these films are very similar to those deposited at higher hydrogen chloride concentrations in the reactant mixture. However, the carrier concentrations in these films, about 10^{17} cm^{-3}, are somewhat higher than those in films deposited by using higher flow rates of hydrogen chloride. This is due presumably to the difference in the incorporation of impurities into gallium arsenide films at different hydrogen chloride concentration. Since the MOS solar cells fabricated from gallium arsenide films deposited at higher flow rates of hydrogen chloride have better characteristics, the use of these experimental conditions has been continued for the deposition of gallium arsenide films.

IV.2. Initial Nucleation of Gallium Arsenide Films on Tungsten/Graphite Substrates

The initial nucleation of gallium arsenide films on tungsten/graphite substrates has been investigated. Gallium arsenide films were deposited at 775°C by using hydrogen chloride at flow rates in the range of 15-45 mℓ/min and an $AsH_3/HC\ell$ molar ratio of 2. The durations of deposition were 15 sec, 30 sec, 1 min, and 3 min. The deposited films were then examined by using a scanning electron microscope. The rate of nucleation and the density of nuclei appear to be rather high. Figures 2 and 3 show respectively the surface of gallium arsenide deposits after 15 and 30 seconds of deposition using a hydrogen chloride flow rate of 45 mℓ/min. About 10% of the substrate surface was covered by gallium arsenide crystallites after 15 seconds of deposition, and about 90% of the surface was covered after 30 seconds of deposition. In both cases, the crystallites are too small to determine if they exhibit any geometries. Figures 4 and 5 show the scanning electron micrographs of gallium arsenide

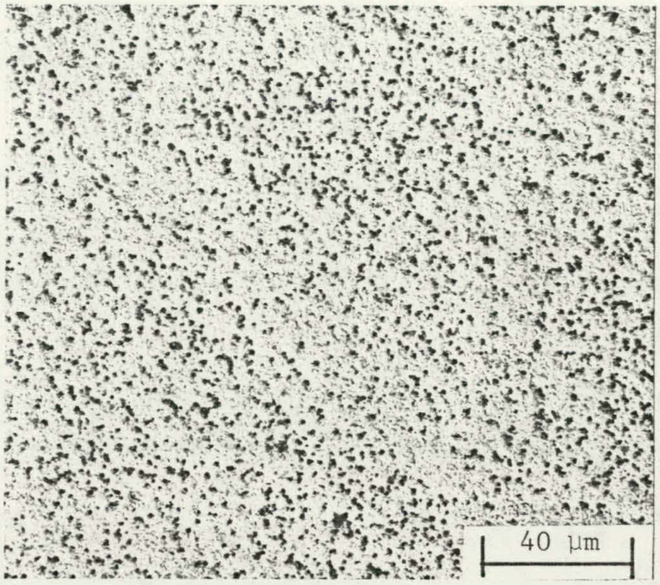

Figure 2 Scanning electron micrograph of the gallium arsenide deposit on a tungsten/graphite substrate after 15 seconds of deposition at 775°C using a hydrogen chloride flow rate of 45 mℓ/min.

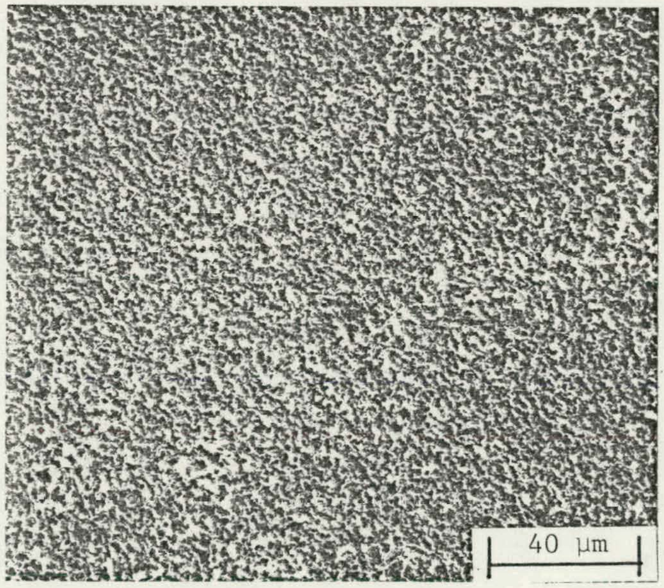

Figure 3 Scanning electron micrograph of the gallium arsenide deposit on a tungsten/graphite substrate after 30 seconds of deposition at 775°C using a hydrogen chloride flow rate of 45 mℓ/min.

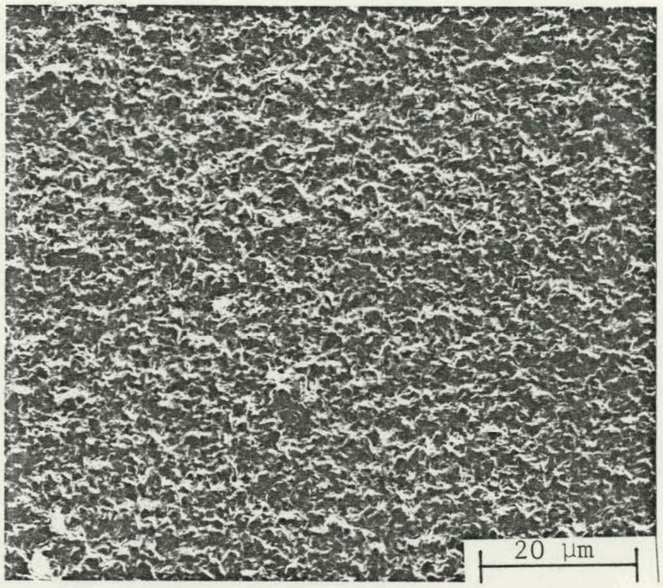

Figure 4 Scanning electron micrograph of the gallium arsenide deposit on a tungsten/graphite substrate after 1 minute of deposition at 775°C using a hydrogen chloride flow rate of 45 mℓ/min.

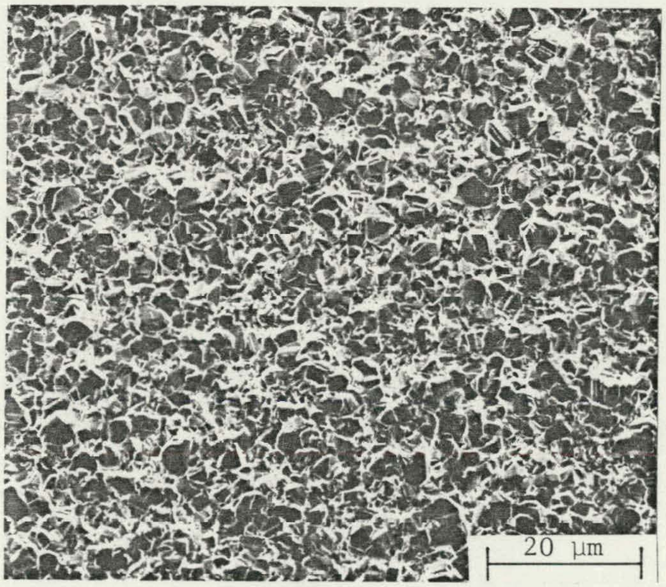

Figure 5 Scanning electron micrograph of the gallium arsenide deposit on a tungsten/graphite substrate after 3 minutes of deposition at 775°C using a hydrogen chloride flow rate of 45 mℓ/min.

films after 1 minute and 3 minutes of deposition, respectively. The gallium arsenide film is continuous after 1 minute of deposition; however, the crystallite size is only of the order of 1 μm. The average crystallite size in gallium arsenide films after 3 minutes of deposition is 2-3 μm. Figure 6 shows the scanning electron micrograph of a gallium arsenide film after 1 minute of deposition using a hydrogen chloride flow rate of 15 mℓ/min. This film is also continuous with crystallite size similar to that shown in Figure 4. Since the gallium arsenide film on tungsten/graphite substrates is continuous after a relatively short deposition time, the use of gallium arsenide/tungsten/graphite structures is a promising approach for the fabrication of thin film gallium arsenide solar cells.

IV.3. MOS Solar Cells

A number of MOS solar cells of the configuration Au/oxide/n-GaAs/n^+-GaAs/W/graphite have been prepared with emphasis on the optimization of the oxidation process and the heavily doped interfacial layer. Gallium arsenide films were deposited on tungsten/graphite substrates at 775°C by using hydrogen, hydrogen chloride, and arsine at flow rates of 1 ℓ/min, 45 mℓ/min, and 90 mℓ/min, respectively, and hydrogen sulfide was used as a dopant during the initial stage of the deposition process to yield a carrier concentration of higher than 10^{18} cm^{-3} in the deposited gallium arsenide. Immediately after the deposition process, gallium arsenide films were oxidized in situ with oxygen at 100-200°C for ½ - 2 hours. This in-situ oxidation assures the formation of a uniform continuous oxide film. The specimen was then transferred, with minimum exposure

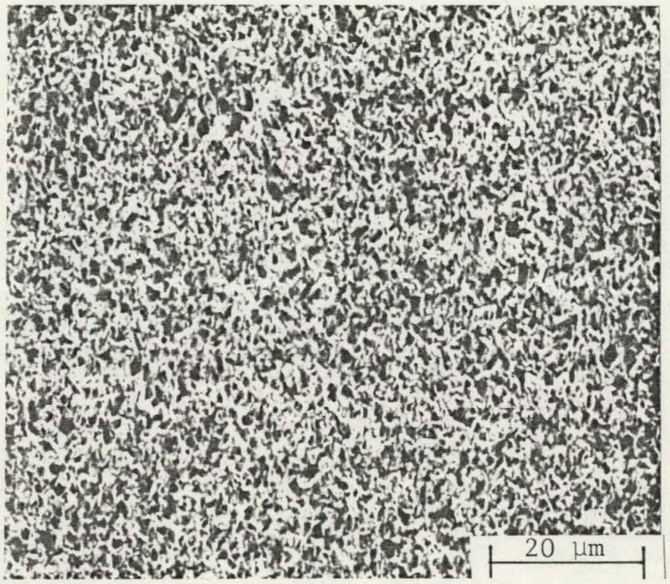

Figure 6 Scanning electron micrograph of the gallium arsenide deposit on a tungsten/graphite substrate after 1 minute of deposition at 775°C using a hydrogen chloride flow rate of 15 mℓ/min.

to air, to a glass tube through which flowed oxygen saturated with water vapor at room temperature at a rate of 100 mℓ/min. The duration of this oxidation was 10-24 hours. Subsequent to the oxidation process, a gold film of 60-70 Å thickness was evaporated onto the surface under a pressure of less than 10^{-6} Torr, and the grid contact was formed by evaporating silver through a metal mask.

The current-voltage characteristics of the resulting solar cells were measured at room temperature in the dark and under illumination with ELH quartz-halogen lamps calibrated with a standard silicon solar cell under AM1 conditions. In general, the initial open-circuit voltage of solar cells prepared from in-situ oxidized gallium arsenide depends strongly on the temperature and duration of oxidation. When the oxidation was carried out at 200°C for 3 hours or longer, the solar cells had open-circuit voltages of 0.5-0.6 V; however, their series resistance was very high due to the excessive thickness of the oxide. When the temperature and/or the duration of in-situ oxidation was reduced, the initial open-circuit voltage and series resistance of the solar cells were lowered. When the surface of gallium arsenide was oxidized by a combination of in-situ oxidation and water vapor treatment, the duration and temperature of water vapor treatment strongly affected the solar cell characteristics. If the water vapor treatment at room temperature exceeded 20 hours, the solar cells always exhibited a high series resistance due to the excessive thickness of the oxide. When the water vapor treatment was reduced to 10-12 hours, the open-circuit voltage was usually above 0.45 V, and the short-circuit current density and fill factor were in the ranges of 10-14 mA/cm^2 and 50-60%, respectively. These solar cells have also been found to be unstable; the open-circuit voltage increased with time, while the short-circuit current density and fill factor remain unchanged. It is possible that the oxide formed by water vapor treatment is hydrated and that the excess water vapor continues to diffuse to the gallium arsenide/oxide interface, generating more oxide.

The thin film gallium arsenide solar cells fabricated in this work is usually of 9 cm^2 in area. At present, the best cell without antireflection coatings has a conversion efficiency of about 3.9% under AM1 conditions, and titanium dioxide coated cells have AM1 efficiencies of higher than 6%. Figure 7 shows the dark current-voltage characteristics of a typical solar cell before and after the application of titanium dioxide coatings. In the forward direction, the diode factor "n" is about 1.4, and the application of AR coating has reduced the saturation current considerably. Also, no appreciable series resistance is apparent at voltages of up to 0.5 V. The reverse current is also reasonable, about 10^{-6}A/cm^2 at 0.5 V after AR coating. Figure 8 shows the characteristics of the above cell under illumination equivalent to AM1 conditions. Prior to the application of titanium dioxide coating, the open-circuit voltage, short-circuit current density, and fill factor were 450 mV, 12.8 mA/cm^2, and 69%, respectively, corresponding to a conversion efficiency of 3.9%. After the deposition of the antireflection coating, the open-circuit voltage, short-circuit current density, and the fill factor were 470 mV, 20.2 mA/cm^2, and 67%, respectively, corresponding to an AM1 efficiency

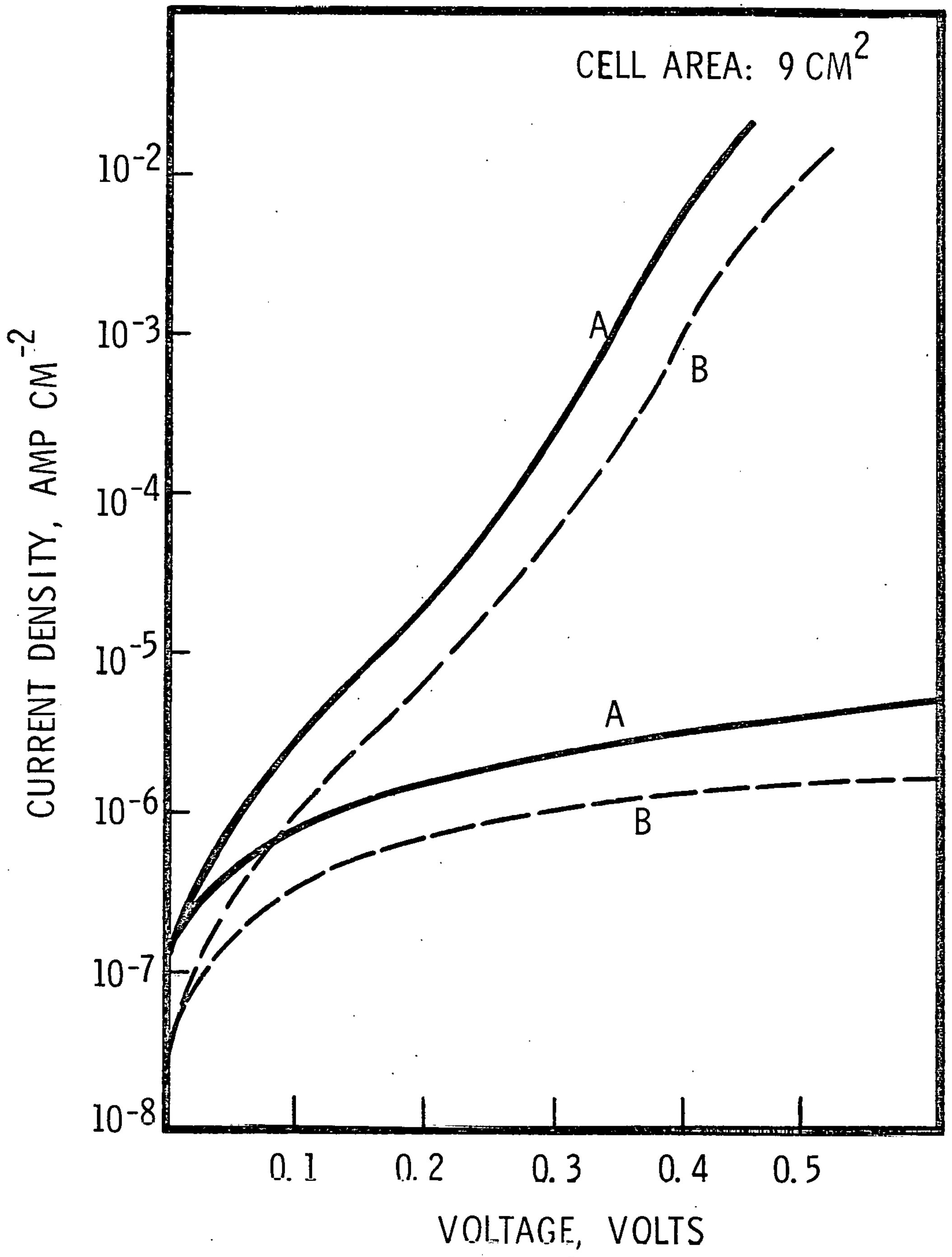

Figure 7 Dark current-voltage characteristics of a Au/oxide/n-GaAs/n$^+$-GaAs/W/graphite solar cell of 9 cm^2 at room temperature before (solid line) and after (dotted line) antireflection coating.

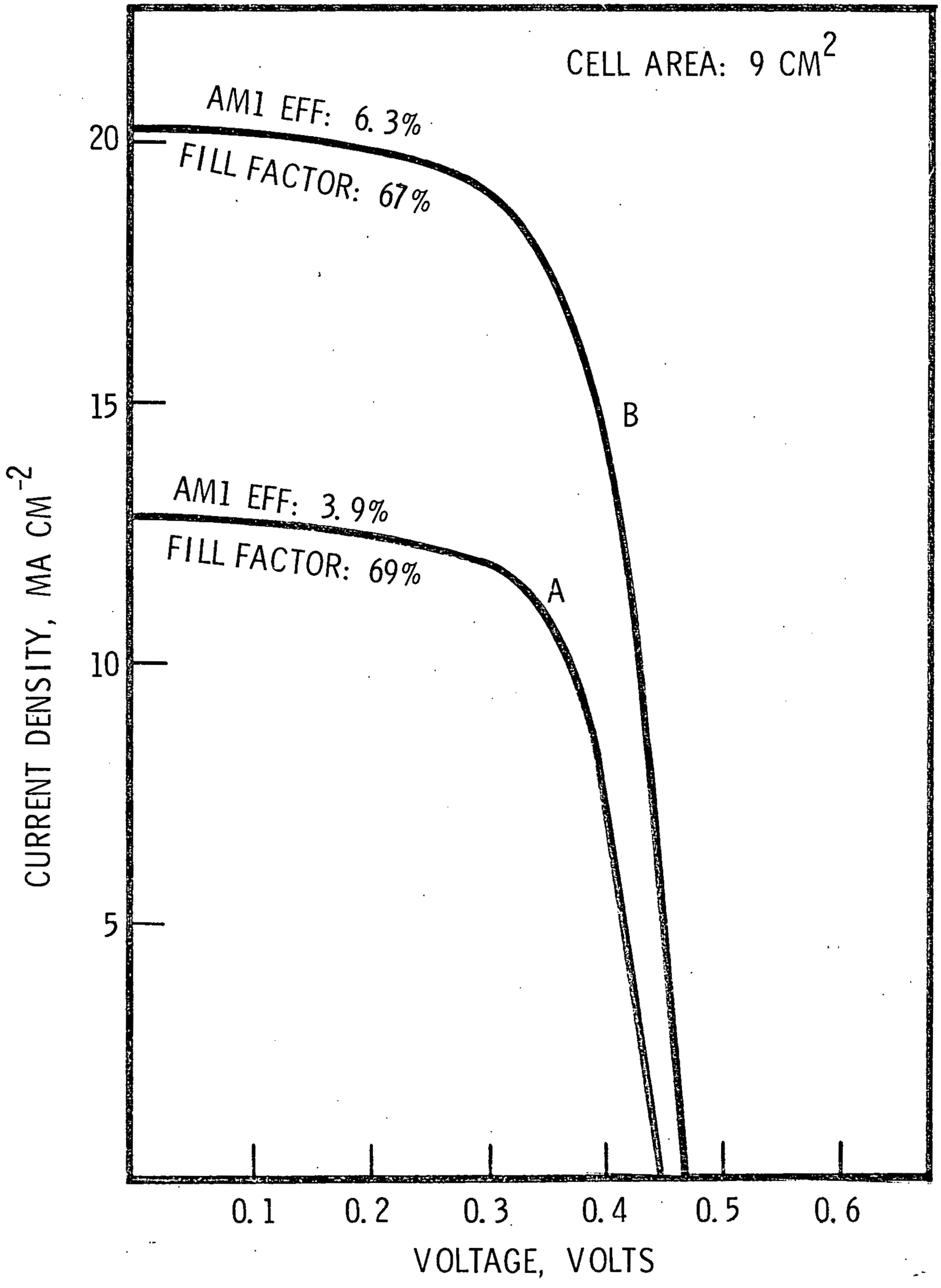

Figure 8 Current-voltage characteristics of the solar cell shown in Figure 7 under illumination with ELH quartz-halogen lamps at AM1 conditions before (curve A) and after (curve B) antireflection coating.

of 6.3%. The deposition of titanium dioxide coating did not result in any instability of the solar cell characteristics.

The spectral response of the solar cell with titanium dioxide coating shown in Figure 7 was measured at 28°C by using a single crystalline silicon solar cell with known spectral response as a reference. One 300 W GE ELH quartz-halogen lamp and interference filters for wavelengths 0.4, 0.45, 0.5, 0.6, 0.7, 0.75, 0.8, 0.85, 0.9 and 0.95 μm were used as the light source. The short circuit currents of the test cell and the reference cell were measured simultaneously at each wavelength. The spectral response of the test cell, in terms of the short-circuit current per unit of monochromatic input power incident on a unit area of the cell, was then calculated. The results are shown in Figure 9. The response peaks at 0.6-0.7 μm, with an external quantum efficiency of 60-70%. The spectral response of this solar cell was also used for the determination of minority carrier diffusion length in gallium arsenide films. The ratio of the measured responses at two wavelengths, 7000 and 7500 Å for example, was compared with the ratios calculated as a function of diffusion length for materials of the same dopant concentration, and the effective diffusion length in gallium arsenide films was found to be 0.5-0.6 μm.

The barrier height in the above solar cell was measured by the photoresponse technique using the surface photovoltage apparatus for silicon solar cells. The photoresponse of the cell was measured in the range of 10,000 and 11,500 Å, and a plot of the square root of photoresponse versus photon energy relation is shown in Figure 10. The barrier height in this cell obtained from the least squares fit method is about 0.96 eV.

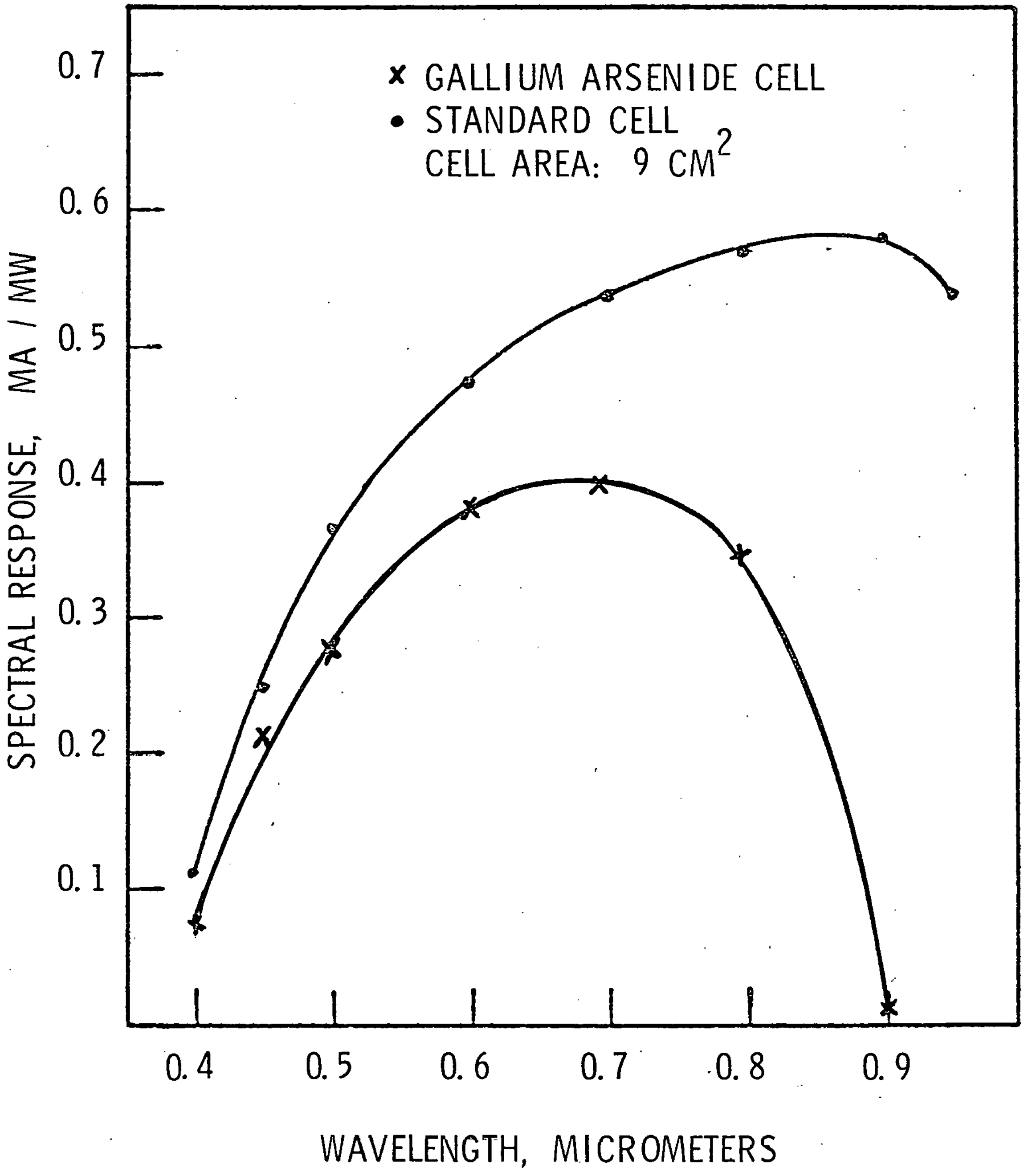

Figure 9 The spectral response of the solar cell shown in Figure 7 after titanium dioxide coating in comparison with a standard silicon solar cell.

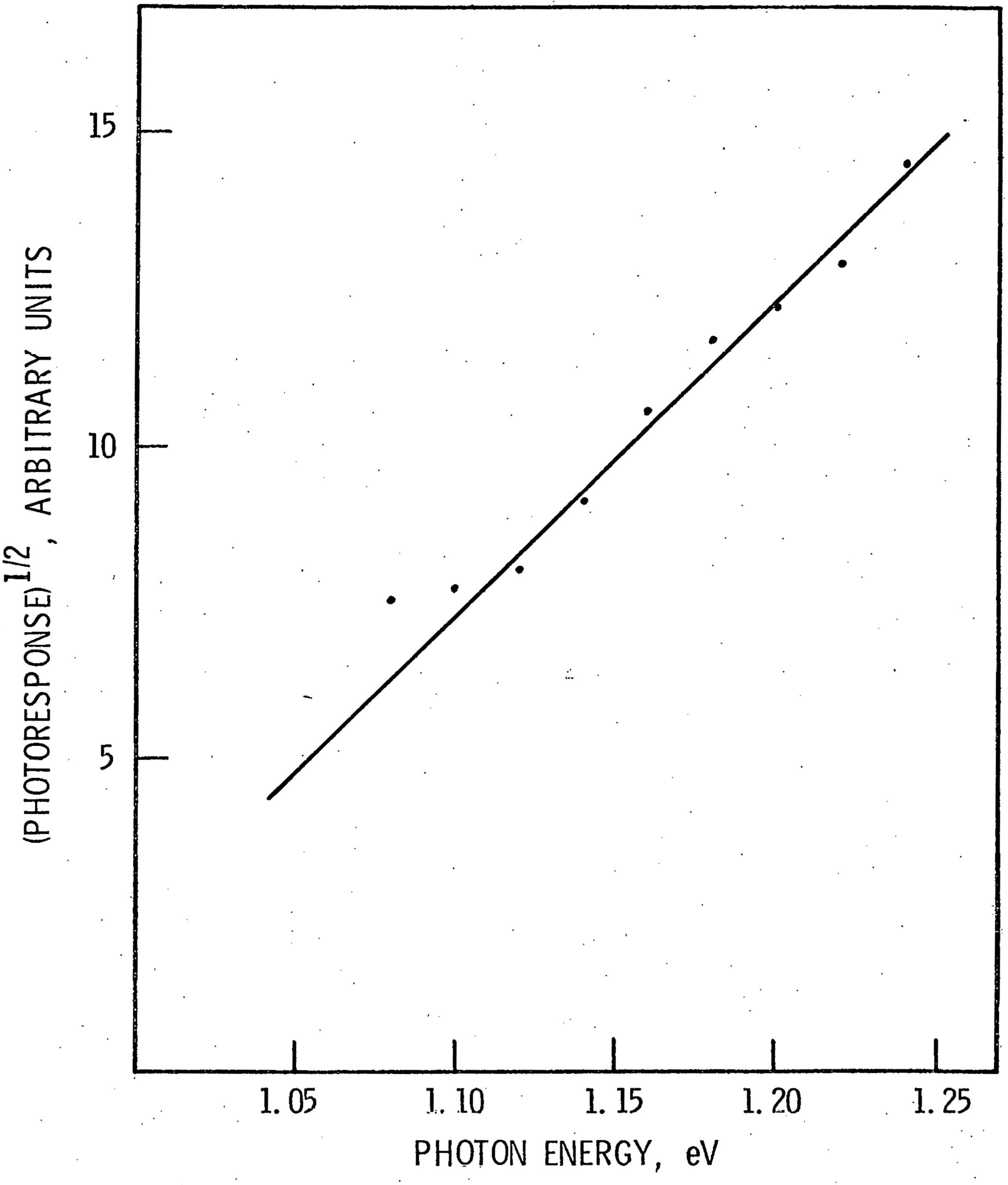

Figure 10 The photoresponse of the solar cell shown in Figure 7 as a function of photon energy.

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VI. Conclusions

1. Gallium arsenide films deposited on tungsten/graphite substrates by the arsenic process are similar to those by the arsine process in electrical and structural properties.
2. Titanium dioxide films are suitable as antireflection coatings for thin film gallium arsenide solar cells, and TiO_2 coated cells exhibit no electrical instabilities.
3. The initial stage of the deposition of gallium arsenide on tungsten/graphite substrates consists of the formation of a high concentration of very small crystallites, and the film is essentially continuous after 1 minute of deposition.
4. Solar cells of 9 cm^2 area of the configuration TiO_2/Au/Oxide/n-GaAs/n^+-GaAs/W/graphite with AM1 efficiencies of higher than 6% can be prepared.

VII. Plan for the Next Period

1. Further investigation of the initial stage of deposition of gallium arsenide films on tungsten/graphite and graphite substrates.
2. Further optimization and characteristics of TiO_2/Au/Oxide/n-GaAs/n^+-GaAs/W/graphite solar cells.
3. Investigation of thermal stability of TiO_2/Au/Oxide/n-GaAs/n^+-GaAs/W/graphite solar cells.
4. Preparation and characterization of thin film gallium arsenide solar cells using silver as the barrier metal.

VIII. Publications

1. "Gallium Arsenide Solar Cells on Tungsten/Graphite Substrates," an extended abstract submitted for presentation at the 153rd National Meeting of the Electrochemical Society.

2. "Thin Film Callium Arsenide Solar Cells on Tungsten/Graphite Substrates," Applied Physics Letters, accepted for publication.