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MIS and SIS Solar Cells on Polycrystalline Silicon

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POLYCRYSTALLINE SILICON

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FOREWORD

This document was prepared as a basis for a critical assessment of the SERI funded programs in the area of MIS/SIS solar cells. Dr. Robert P. Mertens co-authored the publication while on leave from the Katholieke Universiteit in Leuven, Belgium.

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Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

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SUMMARY

Metal-Insulator-Semiconductor (MIS) and Semiconductor-Insulator-Semiconductor (SIS) structured solar cells have been considered a viable alternative to thermally diffused p-n junctions for use on polycrystalline thin-film silicon substrates. Early work indicated that thermal diffusion of a junction in polycrystalline silicon substrates could impose severe problems. Experimental investigations have shown that a p-n junction in polycrystalline silicon can have well behaved characteristics. The major efficiency loss mechanism, introduced by the presence of grain boundaries, apparently does not come from the lower value of shunt resistance but from the additional recombination loss along the grain boundaries. This paper's purpose is to review the status of MIS and SIS solar cell technologies and assess the potential of these structures to meet low cost goals.

Three major types of MIS/SIS solar cells are discussed in terms of structure, materials used in the fabrication, and the current collection under illumination. The types of solar cells discussed include the thin metal MIS structure, the conducting oxide SIS structure, and the MIS inversion layer device. The specific advantages of a MIS/SIS solar cell are investigated by the use of theoretical calculations. The spectral response, short circuit current, open circuit voltage, fill factor, and cell efficiency have been calculated for the MIS/SIS case, the advanced diffused, and standard diffused solar cells.

Several specific problem areas exist with these devices. The possible loss mechanisms in the MIS/SIS device are detailed, the cell stability and degradation mechanisms are identified, and the fabrication techniques amenable to large scale use are discussed. A major conclusion of the paper is that the MIS/SIS solar cells have no apparent advantage over diffused p-n junctions.

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SECTION 1.0

INTRODUCTION

Metal-Insulator-Semiconductor (MIS) and Semiconductor-Insulator-Semiconductor (SIS) structured solar cells have been considered a viable alternative to thermally diffused p-n junctions for use on polycrystalline thin-film silicon substrates. These beliefs are based on the fact that problems can arise during the junction formation by thermal diffusion on polycrystalline silicon. Also, the MIS and SIS type devices can possibly be manufactured in a less expensive way than diffused cells. Early work revealed that thermal diffusion of a junction in polycrystalline silicon substrates could impose severe problems. These problems are due to a possible enhanced diffusion along the grain boundaries introducing current leakage paths. These leakage currents result in low shunt resistance and a reduced value of the cell fill factor. However, several groups have reported diffused junction characteristics [1, 2, 3] of cells on polycrystalline silicon substrates with good values of fill factor. These recent reports indicate that excessive values of leakage currents can be overcome. The major efficiency loss mechanism, introduced by the presence of grain boundaries, appears to come not from the lower values of shunt resistance but from the additional recombination loss along the grain boundaries [4, 5]. The resultant effects are lower values of the short circuit current and, to a smaller extent, the open circuit voltage. Considering the problems of recombination loss at the grain boundaries, no direct major advantage of using an MIS or SIS structure seems to exist. Many of the fabrication techniques for these cells appear to be batch type vacuum processes that are less amenable to large scale production. An exception to the batch type fabrication processing is the recently developed spray deposition process of transparent oxide semiconductors [6].

This paper's purpose is to review the status of MIS and SIS solar cell technology and to assess the potential of these structures to meet low cost goals. Initially, the paper describes the commonly used MIS and SIS structures. The third section presents the general advantages of MIS and SIS structured solar cells in terms of use with polycrystalline silicon substrates with emphasis on the enhanced blue response of these cells. The general problem areas are described in the fourth section. The following section concerns a study of the relative advantages and disadvantages of the different MIS and SIS solar cell structures and summarizes the results achieved to date. The final section summarizes the paper and presents some conclusions.

SECTION 2.0

MIS AND SIS SOLAR CELL STRUCTURES

Three major MIS or SIS type solar cell structures have been proposed. In the first type shown in Figure 2-1(a), the collecting barrier is formed by a thin-metal/thin-oxide silicon structure. The thin metal layer is made semi-transparent to visible radiation by keeping its thickness around 50 Å. There exists an electrical resistivity/optical transmittivity tradeoff of the thin metal layer, and the thickness chosen is usually a compromise value. Problems with electrical sheet resistance could be overcome by adequate contact grid metalization, but this could add a significant price increase if photolithographic steps are needed for fine line geometries. The thin insulating oxide layer is typically between 15 Å and 30 Å. This layer's purpose is to block the majority carrier currents injected into the metal at forward bias from the semiconductor while still being transparent to the photogenerated minority carrier current, and thereby increasing the open circuit voltage. The oxide layer also reduces the surface recombination velocity by several orders of magnitude. Once collected, the photogenerated carriers travel through the thin metal layer and along the silicon surface. The carriers can be collected by the thick metal grid pattern present on top of the thin metal layer. The thick metal grid is similar to those used on conventionally diffused junction cells. The collecting barrier is brought about by the difference in work function between the thin metal and the underlying silicon. The barrier height is also influenced by the properties of the thin oxide. The highest efficiencies (13.1% active area, AM1) have been achieved with low-work function metals such as Al, Ti, or Cr on p-type silicon [7, 8, 9] (Table 2-1). In this case, the surface under the thin oxide layer is inverted, and an n^+ layer is induced into the silicon. These cells can be described as n^+/p cells. The thin oxide layer is transparent for the electron flow (minority carriers) in both directions, but it forms a barrier for the hole current flow.

In the SIS type cell shown in Figure 2-1(b), the collecting barrier is formed by the difference in work functions between the conductive semiconductor oxide and the silicon. Specific advantages of conductive, transparent semiconductor oxides, such as ITO, SnO_2 or Cd_2SnO_4 , include:

- Index of refraction matching to provide antireflection properties,
- minimal visible absorption in the oxide layer due to the wide bandgap semiconductor, and
- oxide films which can be deposited at low temperatures so that interdiffusion can be minimized and an abrupt junction can be formed.

The conductive oxide provides a lateral current path along the surface that allows the minority carriers, generated in the bulk and collected by the surface barrier, to reach the contact grid. The thin insulating oxide introduces the same beneficial effects in the SIS device as the thin metal MIS type structure. The highest efficiencies with SIS type cells have been obtained with indium-tin-oxide (ITO) [10] on p-type silicon and with tin-oxide (SnO_2) on n-type silicon [6]. Cell efficiencies of 14.0% and 12.0%, respectively, have been achieved with these cells (Table 2-1). One major problem with the conductive oxide ITO is that the work function can change as an unknown function during the fabrication process. These changes in work function can affect the Fermi level position in the oxide, the degeneracy and resistivity of the oxide films, and hence, the final efficiency of the device.

Figure 2-1a. MIS with Transparent Metal Film

Figure 2-1b. MIS with Conductive Oxides

Figure 2-1c. MIS Grating Inversion Layer Cell

Figure 2-1. Cross Section of the Three MIS/SIS Structures

Table 2-1. CURRENT STATUS OF MIS/SIS TECHNOLOGIES

	Technology	Material	Area _g (cm ²)	Voc (mV)	J _{sc} (ma/cm ²)		Fill Factor (Percent)	Efficiency (Percent)		Source
					Active	Total		Active	Total	
Thin Metal MIS	Chromium	Single, p	2.0	570	34.0		68	13.1		7
	Chromium	Wacker ^a , p	2.0	500	24.2		73	8.8		7
	Titanium	Single, p	2.6	550		33 ^b	65		11.8 ^b	8
	Aluminum	Single, p	1.5	515		27.5	65		9.1	32
SIS	ITO, Ion Beam	Single, p	1.36	587		32.5	74		14.0	10
	ITO, Ion Beam	Wacker, p	2.6	542		24.9	71		9.5	10
	ITO, Ion Beam	Single, p	2.07	518	31.0		72	12.0		33
	ITO, Ion Beam	Montanto ^c , p	3.93	462	20.9		68	6.6		33
	MoO ₃ , Ion Beam	Single, p	0.04	225	14.6		53	1.7		34
	ITO, Spray	Single, n	3.94	590		28.3	66		11.1	35
	ITO, E-Beam	Single, n	4.0	485		30.3	67		9.8	30
	SnO ₂ , spray	Single, n	3.84	615		29.0	68		12.1	6
	SnO ₂ , spray	Wacker, n	4.0	560		26.6	68		10.1	6
	SnO ₂ , E-Beam	Single, n	4.0	590		29.0	65		11.1	18
	Cd ₂ SnO ₄ , Ion Beam	Single, p	-	500	31.8		53	8.4		10
	ITO, spray	Single, n	0.3	520	31.5		70	11.5		36
	ITO, spray	Wacker, n	3.75	500		29.0	71		10.3	37
	Aluminum, (SiO)	Single, p	3.0	642	35.6		77	17.6		11
	Aluminum, (SiO)	Wacker	3.1	558	30.8		73	12.5		38
Diffused Junction	Phosphorous diff.	Semi Crys., p	4.0	600		34.5	78		16.1	2
	Phosphorous diff.	Wacker, p	4.5	542		27.9	77		11.6	39

^aThe "Wacker" material refers to polycrystalline casted material.

^bThe J_{sc} or efficiency column numbers present in the center indicate that an active or inactive area has not been defined.

^cThe "Montanto" material refers to single pass float zone refined polycrystalline silicon.

^dIncluded for comparison purposes only.

The operation of the grating MIS cells shown in Figure 2-1(c) relies on the induction of an inversion layer by the fixed charge present in the insulating oxide deposited onto the silicon. The insulating oxide serves as an anti-reflection coating on the silicon. The inversion layer acts as a collecting barrier for the photogenerated minority carriers, and the collected carriers travel through this layer. The MIS structure present under the grid acts as an ohmic contact to the inversion layer. Since the active part of MIS grating cells is not covered by metal layers, no transparent metal layers are required. The highest efficiencies obtained to date (17.6% active area, AM1) with the MIS or SIS structured silicon solar cells have been reported for MIS grating cells [11] (Table 2-1). One explanation for these high efficiency values is that the inversion layer cell operates like an ideal p-n junction device. The thin oxide layer is not nearly as critical in this type of device so long as it does not provide a tunnel barrier to photogenerated carriers.

SECTION 3.0

GENERAL ADVANTAGES OF MIS AND SIS TYPE SOLAR CELLS ON POLYCRYSTALLINE SUBSTRATES

The original reasons why MIS/SIS type barriers on polycrystalline silicon were preferred over diffused junctions were the absence of leakage currents associated with enhanced grain boundary diffusion and the potentially less expensive fabrication processes. However, more detailed studies have proven these original reasons to appear somewhat invalid. Indeed, enhanced recombination of minority carriers, not the leakage and shunting problems, seem to be the major difficulty associated with grain boundaries in polycrystalline substrates. In addition, several of the MIS/SIS type cells involve costly batch type vacuum fabrication processes less amenable to large scale production and more expensive than diffusion technology. This, of course, is not true in the case of the high through-put, oxide semiconductor spray technologies.

Claims exist that MIS/SIS type cells could yield higher open circuit voltages than diffused cells [12] since, by proper choice of the metal work function, the dark forward current injected from the substrate into the metal could be reduced or completely eliminated. The corresponding current in diffused cells, injected from the substrate into the diffused layer, limits the open circuit voltage in high quality single crystal cells [13]. On the other hand, since in polycrystalline films one deals with smaller diffusion lengths in the substrate, due to enhanced recombination in and near the grain boundaries, the open circuit voltage will mainly be limited by the current injected from the emitter into the substrate. Since this current is identical in a diffused or MIS/SIS cell, substantially higher V_{oc} values for MIS/SIS type cells on polycrystalline films cannot be expected.

However, conventionally diffused cells still suffer from a disadvantage related to the presence of a dead layer in the upper part of the diffused region [14]. This dead layer causes a fall-off of the quantum efficiency in the UV part of the solar spectrum. Since the transition from single to polycrystalline substrates mainly causes a loss of the quantum yield for longer wavelengths through a reduction of the diffusion length, it is clear that the enhancement of the blue response of a cell is relatively more important on poly than on single crystal silicon. Due to the absence of a dead layer in an MIS/SIS type cell, this type of cell inherently has an improved blue response. Therefore, it seems important to determine the potential increase in the air mass one (AM1) efficiency by going from a diffused cell to an MIS/SIS type using polycrystalline silicon substrates.

To make the necessary calculations to clarify this point, it was assumed that a 25 μm thick polycrystalline silicon, p-type thin film was deposited onto a foreign substrate. A 25 μm thick silicon film was chosen for these calculations due to the trade-off between optical integrity and material usage. All grain boundaries were assumed to be columnar or perpendicular to the substrate. The grain size was varied between 25 μm and 6.4 μm . All short circuit currents, open circuit voltages, and fill factors have been calculated as a function of grain size for a standard diffused junction, an advanced diffused cell, and an MIS or SIS type cell. The major characteristics of the structures are listed in Table 3-1.

Table 3-1. CHARACTERISTICS OF THE THREE TYPES OF POLYCRYSTALLINE SILICON SOLAR CELLS

Characteristics	Types of Solar Cells		
	Standard Diffused	Advanced Diffused	MIS
N_A (Acceptor Concentration in the Film)	$10^{16} \text{ (cm}^{-3}\text{)}$	$10^{16} \text{ (cm}^{-3}\text{)}$	$10^{16} \text{ (cm}^{-3}\text{)}$
Junction depth	$0.3 \mu\text{m}$	$0.1 \mu\text{m}$	0
Dead layer thickness	$0.125 \mu\text{m}$	$0.005 \mu\text{m}$	0
D_n (cm^2/s)	25	25	25
Depletion layer thickness	$0.3 \mu\text{m}$	$0.3 \mu\text{m}$	$0.3 \mu\text{m}$

3.1 Calculation of the Short Circuit Current

Following Lindmayer and Allison [14] the assumption has been that all carriers generated within the dead layer are lost, and those carriers generated in the diffused layer outside of the dead layer and in the depletion region are collected. Both cases of infinite and zero recombination velocity at the silicon film/substrate interface have been assumed. The latter case refers to a cell with a backsurface field. To correlate diffusion length and lifetime with grain size, the empirical formula proposed by Ghosh [15] has been used:

$$\tau = 5 \times 10^{-6} \times \text{grain size in cm} \quad (\text{seconds}) \quad (1)$$

Although no strong theoretical background for this formula for large grain size material is apparent, it fits the experimental data reasonably well for grain sizes in the range $100 \mu\text{m}$ to $10,000 \mu\text{m}$.

Assuming zero reflection loss and zero absorption loss in the thin metal films or antireflection oxides, the quantum yield of the three structures can now be calculated as a function of grain size in a straight forward manner. The results of these calculations are presented in Figure 3-1. As expected, the three structures have identical red responses whereas significant differences exist in quantum yield in the short wavelength regions.

The AM1 short circuit current follows from the quantum yield and the solar energy spectral distribution. To take reflection losses into account, a constant wavelength independent reflection loss of five percent has been assumed for all structures. This loss overestimates to some extent the advantage of blue enhanced cells. The calculated short circuit current density, per unit area of active surface area as a function of grain size, is given in Figure 3-2. Clearly a significant improvement in the AM1 short circuit current density can be expected by going from standard to very shallow diffusions. However, the difference in short circuit current between an advanced diffusion and an MIS/SIS cell seems marginally small.

Figure 3-1. Quantum Yield of MIS, Advanced and Standard Diffused Cells, 25 μm Thick Film, no BSF

Figure 3-2. Short-Circuit Current as a Function of Grain Size, 25 μm Thick Film, No BSF

3.2 Calculation of the Open Circuit Voltage

Two components of the dark current have been considered: the recombination current in the space charge region and the diffusion-recombination current in the neutral base. For diffused cells, the current injected into the diffused layer has been disregarded. Also, for MIS/SIS type cells the current injected from the substrate into the metal or conductive oxide has not been considered. This assumption seems reasonable because of the smaller diffusion lengths in poly materials. The total dark current density then equals:

$$J = J_{o(dif)} \exp \frac{qV}{KT} + J_{o,(rec)} \exp \frac{qV}{2KT} \quad (2)$$

where:

$$J_{o,(dif)} = \frac{qD_n n_i^2}{L_n N} \coth (H/L_n) \quad (3)$$

$$J_{o,(rec)} = \frac{qn_i W}{2} \quad (4)$$

for an infinite recombination, and

$$J_{o,(dif)} = \frac{qD_n n_i^2}{L_n N} \coth (H/L_n) \quad (5)$$

for a zero recombination velocity at the film-substrate interface. The definition of the symbols is given in Table 3-2.

Table 3-2. DEFINITION OF THE SYMBOLS

Symbol	Meaning	Units
q	Electronic charge	coulomb
D_n	Diffusion constant of electrons in the base	$\text{cm}^2/\text{seconds}$
n_i	Intrinsic concentration	cm^{-3}
L_n	Diffusion length of electrons in the base	μm
N	Impurity concentration in the base	$\#/\text{cm}^3$
H	Thickness of the silicon film	μm
W	Depletion layer width	μm
τ	Minority carrier lifetime	seconds
V	Applied forward bias voltage	volts

By equating expression 2 to the value of short circuit current, the open circuit voltage (V_{oc}) can be determined. Figure 3-3 shows V_{oc} as a function of grain size for the standard diffused, advanced diffused and MIS/SIS type solar cells. The open circuit voltage of the advanced diffused cells turns out to be nearly identical to the values found for MIS/SIS type cells.

3.3 Calculation of the Fill-Factor

The maximum power point for the different cells has been calculated using the values obtained from the I_{sc} and using Eq. 2. To take series resistance into account, the results were multiplied by a constant factor 0.93. According to the calculations of Hovel [16], a series resistance of 1 ohm for a 1 cm² silicon solar cell, drops the value of efficiency by 1% (15% to 14%), which corresponds to a 7% reduction in cell output. Thus, for a well designed solar cell, losses of this magnitude due to series resistance is a reasonable assumption. Results indicate only minor differences in fill factor exist for the three structures. This common value is given on Fig. 3-4.

3.4 Calculation of the Efficiency

AM1 efficiencies have been obtained multiplying I_{sc} , V_{oc} , and the fill-factor. To compensate for grid coverage, the active area efficiency has been multiplied with a constant factor 0.92. This figure takes into account a typical 8% coverage to obtain the total area efficiency and is represented in Figure 3-5 as a function of grain size. Figure 3-5 clearly indicates the sizeable effect of the back-side recombination velocity on the efficiency of thin film (25 μ m) silicon cells as already determined by Hovel [16]. The calculations indicate that a back surface field type of structure is necessary to obtain 10% total area efficiency.

Due to the relatively larger importance of the blue part of the solar spectrum on polycrystalline films, blue enhanced cells yield considerably larger efficiencies than standard diffused cells. Standard diffused cells require four-times-larger grain sizes than blue enhanced cells to obtain 10% efficiency. To date, 9.7% efficient cells have been achieved on thin film (25 μ m) silicon by standard diffusion technology. The grain size in these cells was estimated to be $\approx 1-5 \mu$ m [3].

Blue enhancement can be obtained by violet cell type diffusions or MIS/SIS type cells with metals or oxides as transparent as possible for the blue part of the spectrum. Since shallow diffusions are very critical on polycrystalline substrates, results may indicate that one of the MIS structures is more suitable to obtain blue enhancement on polycrystalline substrates. This increase supposes that the thin metals or oxides do not absorb the blue light present in the solar spectrum and, consequently, rules out the use of oxides such as SiO₂. For this latter oxide, the better intrinsic blue response of an MIS structure is largely lost because of the rather strong blue absorption. The better response assumes that the loss mechanisms described in the next section will be solved.

In addition to the better blue response, MIS/SIS type cells offer the advantage of a low temperature fabrication process. This process could be very advantageous if some grain boundary passivation technique is used prior to the cell fabrication. For a diffused cell made on such material the passivation effect could be lost during the high temperature step associated with the diffusion. On the other hand, diffused cells are compatible with passivation techniques implemented as the last step of the process.

Figure 3-3. Open-Circuit Voltage as a Function of Grain Size, 25 μm Thick Film, No BSF

Figure 3-4. Fill-Factor as a Function of Grain Size 25 μ m Thick Film, No BSF

Figure 3-5. Efficiency vs. Grain Size, 25 μ m Thick Film, With and Without BSF

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SECTION 4.0

GENERAL PROBLEM AREAS WITH THE MIS/SIS STRUCTURE

Several areas exist that raise questions on the potential feasibility of the MIS/SIS type device for large scale terrestrial applications. In general, experimental MIS/SIS cell efficiencies have been below values obtained by theoretical analysis as done in the previous section, and below those achieved with the diffused junction technology. Speculation is possible on the reasons for this inconsistency. Loss mechanisms in the MIS/SIS type device that could account for the lower values of efficiency include:

- the relative immaturity of the MIS/SIS solar cell technology in regards to the advanced state of the thermal diffusion processes;
- transmission-reflection-absorption of visible light associated with the thin metal or conducting oxide layer;
- incomplete coverage of a polycrystalline silicon surface by the thin metals due to grain boundary misorientations otherwise known as "step coverage;"
- work function variations in the deposited oxide semiconductors as a result of different fabrication techniques and parameters;
- difficulty in obtaining precise control over the thin insulating interfacial layer; and
- changes in the Fermi level position in oxide semiconductors or in the insulating oxide charge storage which affect the degree of silicon inversion.

Many of these problem areas have yet to be addressed in the research of the MIS/SIS type devices. Thus, the technology is far behind that of thermal diffusion.

Another questionable area is that of these cells' long-term stability. Many researchers report rapid degradation under stress conditions of light, bias, and temperature [17-20]. Several degradation mechanisms exist for these cells, but the most important seems to be oxygen diffusion through the thin metal or conducting oxide and the subsequent growth of the thin interfacial layer [21]. This mechanism has been determined by elevated temperature tests inside and outside high vacuum chambers. Also, instability caused by humidity trapped in the thin oxide before metal deposition has been reported [22], but this type of instability can be avoided by using a dry oxygen process. Another possible degradation mechanism for the oxide semiconductor cells is a slowly varying configuration of the oxide semiconductor [18]. This mechanism could alter the electrical and optical properties of these thin films. The data on the degradation mechanisms in these cells is incomplete, and no conclusive statement on cell stability can be made at this time.

In the present research of MIS/SIS devices, most techniques use some type of batch-vacuum process that can be less amenable to large scale production. Vacuum steps in the cell fabrication processes are costly and somewhat energy intensive. However, the possibility of using continuous flow processes must not be excluded as indicated by the use of spray techniques [6]. The MIS/SIS system, unlike the diffused junction, is critically sensitive to interfacial state densities [23]. This problem is critical because, like the interfacial layer itself, it is very difficult to control. Recent research concluded that surface state densities can be changed by surface etching, surface preparation, and the

type of silicon used [24]. Also, the density of surface states could be affected by fabrication procedures such as direct ion-beam milling of the silicon surface [25].

The MIS grating solar cell requires fine line geometry. These geometries are usually achieved by photolithographic techniques. Photolithographic steps in a large scale production situation possibly may not meet low cost goals. On the other hand, the possibility should not be excluded that the fixed charge in the oxides could be enhanced by chemical treatment. Thus, the finger spacing could be wider, and other metallization techniques could be utilized.

The final general problem area to be addressed is that of cell yield or fabrication repeatability. Unlike the methods of thermal diffusion where most wafers per batch are identical, most MIS/SIS fabrication techniques have shown wide variation in solar cell parameters from run to run. This is often true even when identical fabrication parameters are used. These problems must be solved before MIS/SIS cells can be produced in reasonable quantities.

SECTION 5.0

RELATIVE ADVANTAGES AND DISADVANTAGES OF THE MIS/SIS STRUCTURE

This section compares the relative merits of each structure; thin metal MIS, conducting oxide SIS, and grating MIS, and summarizes the results achieved to date.

A strong trade off exists with thin metal MIS cells between sheet resistance and optical transmission. Obviously, the thicker the metal, the lower the electrical sheet resistance, but there is a subsequent reduction in optical transmission. This trade-off suggests a metal thickness to obtain optimum performance. In the transparent conductive oxide SIS cells, this problem is reduced considerably. Because the optical properties of the oxide films are relative independent of film thickness, the electrical sheet resistance can be minimized by depositing a thick film. Although thick oxide films can solve some problems, the thicker film may need an additional anti-reflection coating to achieve lower reflection losses [26]. The MIS grating cell appears to be best considering these parameters. Because of the nature of the thick contact grid pattern, there is no optical transmission/sheet resistance trade off. Of course, with this cell structure, additional photolithographic steps may be necessary.

Variations in the work function of metals and oxide semiconductors can have deleterious effects on the cell performance. In the thin metal MIS-type device, the work function can fluctuate up to ≈ 1 eV depending upon the thickness and evaporation rate of the film [27]. Similar problems exist in the fabrication of oxide semiconductors. In the case of ITO, several methods for deposition; i.e., ion-beam sputtering [28], dc and rf sputtering [29], electron-beam deposition [30], and spray technology [6] have all been utilized in the fabrication of solar cells. Efficient solar cells have been fabricated by several methods on both n- and p-type silicon. These results indicate that the ITO work function is strongly dependant upon the fabrication technique and the parameters used during the reactive sputtering. In some preliminary measurements on the photoemission spectra of SnO_2 deposited on silicon, the emission spectra has been shown to change by up to ≈ 0.5 eV depending on the deposition and surface preparation techniques [31]. Finally, in the MIS grating type solar cell, the metal grid pattern is usually thick enough to have properties of the particular bulk metal. Aspect ratios of four to one can easily be achieved. As a result, there is no work function variation of the metal.

Results by many research groups are summarized in the Table 2-1. The initial results indicate that the highest AM1 Voc to date in silicon (655 mV) has been achieved with an MIS grating device [11]. One notices that the thin metal MIS has J_{sc} limitations, probably due to reduced optical transmission. Also, the drop in efficiency from MIS/SIS single crystal to polycrystalline is larger than expected. Finally, of all the MIS/SIS results presented (which represent the best to date), the cell efficiencies are not really any better and are actually slightly worse than those of the diffused junctions. Theoretically, cell efficiencies of the MIS/SIS structure should be better than those of the diffused junction technology, but the results to date have been rather disappointing.

SECTION 6.0

CONCLUSIONS

The principle advantages of the MIS/SIS technology are a potentially better blue response than diffused cells and a low temperature fabrication process. Blue enhancement obtained in diffused cells by using very shallow junctions probably will cause some severe problems if polycrystalline materials are used. Therefore, an MIS/SIS type cell might be an economical alternative to obtain a high short wavelength response.

The advantage of a low temperature process is apparent when polysilicon materials are used which have been grain boundary passivated prior to cell fabrication. Such materials would probably exclude any high temperature cell fabrication process. This advantage is irrelevant if the passivation is done after junction fabrication.

Literature often claims that MIS/SIS solar cells are simpler to make than diffused cells. A detailed look at these fabrication techniques reveals that, in general, they are more complex than those of the pn junction technology. Thus, conversion to MIS/SIS is not cost effective unless a non-vacuum process is utilized.

Apparently, MIS/SIS technologies will be economically competitive only if their efficiencies in a production environment are higher than those of diffused cells. Although the theoretical efficiency of MIS/SIS cells is somewhat higher than diffused cell efficiencies, the values actually measured in practice are considerably lower. Therefore, the achievement of repeatable high efficiencies remains a prime objective. Other important specific studies include degradation mechanisms, interfacial oxide properties and formation, work function measurements, conductive oxide reaction mechanisms, and an analysis of fabrication techniques amenable to large scale product. These types of studies are necessary before highly efficient MIS/SIS devices can consistently be obtained.

SECTION 7.0

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