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N86-12767

Interconnect Resistance of Photovoltaic Submodules

Prepared for

JPL Research Forum
on

Reliability and Engineering of
Thin-Film Photovoltaic Modules

by

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Interconnect Resistance in Submodules

Small area amorphous silicon solar cells generally have higher efficiencies than large interconnected submodules. Among the reasons for the differences in performance are the lack of large area uniformity, the effect of non-zero tin oxide sheet resistance, and possibly pinholes in the various layers. Another and usually small effect that can contribute to reduced performance of interconnected cells is the resistance of the interconnection i.e. the series resistance introduced by the metal to tin oxide contact through silicon.

Our 1' X 1' and 1' X 3' PV panels have tin-oxide to aluminum contacts that are approximately 0.01cm wide and nominally 30 and 142 cm long for the two different sized panels (approximately 0.4 cm inactive edges are allowed for see Figure 1). To a first approximation the effect of the contact resistance is simply that of a series resistance; this is easily calculated and is shown in Figure 2. Here the fill factor is calculated using the ideal diode equation for tin oxide sheet resistances of 5 and 20 ohms per square.

There is another effect which can, under certain circumstances, be important. It is due to small parasitic cells resulting from the patterning of the submodule. A schematic representation of the cross section of a portion of a monolithic submodule is shown in Figure 3. Also shown is the electrical schematic for a cell and its interconnect region. This interconnect scheme results in a main cell with area, A3 and two small cells with areas A1 and A2. The two small cells are in parallel and are shunted by the contact between the tin oxide and aluminum with contact resistance Rc. In the ideal case where tin oxide to aluminum contact resistance is zero, the only detrimental effect of the two small cells is to reduce the effective area of the large cell. In this case in addition to the approximately 0.03cm lost to the three patterning operations another 0.05cm (the width of A1 + A2) is lost due to the parasitic cells. If however Rc is not zero then additional losses result, their extent depending on the magnitude of Rc and the areas A1 and A2. Figure 4 shows approximately how to output characteristic of the total cell is changed by a fairly high Rc. Here curve A is the I-V curve for the combination of A1 and A2, curve B is that of the main cell, A3 and curve C is the resultant curve due to all three. In the open circuit condition, the large cell is not loaded; the small cells however are shunted by Rc and for not excessively large Rc, their I-V curve is a straight line with an open circuit voltage of Vsoc. This voltage subtracts form the open circuit voltage of the large cell, Vloc, to give a measured open circuit voltage, Vmoc, of Vloc-Vsoc. If Is is the short circuit current of the small cells, then clearly the contact resistance is given by Vsoc/Is. To obtain a value for Rc we need to know Is and we assume it to be proportional to the short circuit current of the large cell, Il, as is the area. We can obtain Vloc by shading the two small cells from light (in this condition the small cells produce no current). Thus

$$Rc = \frac{Vloc - Vmoc}{Il} \times \frac{A3}{(A1+A2)}$$

It might appear that a simple way to reduce Rc is to make the contact wider. Simple calculations show that is not very effective unless Rc is very high. In Figure 5 the equivalent circuit for a tin oxide to aluminum contact is shown. Here W is the contact width, Rsh is the tin oxide sheet resistance and ρc is the specific contact resistivity in cm2. The linear effective contact resistance Rceff in cm can be obtained from this model in closed form and is

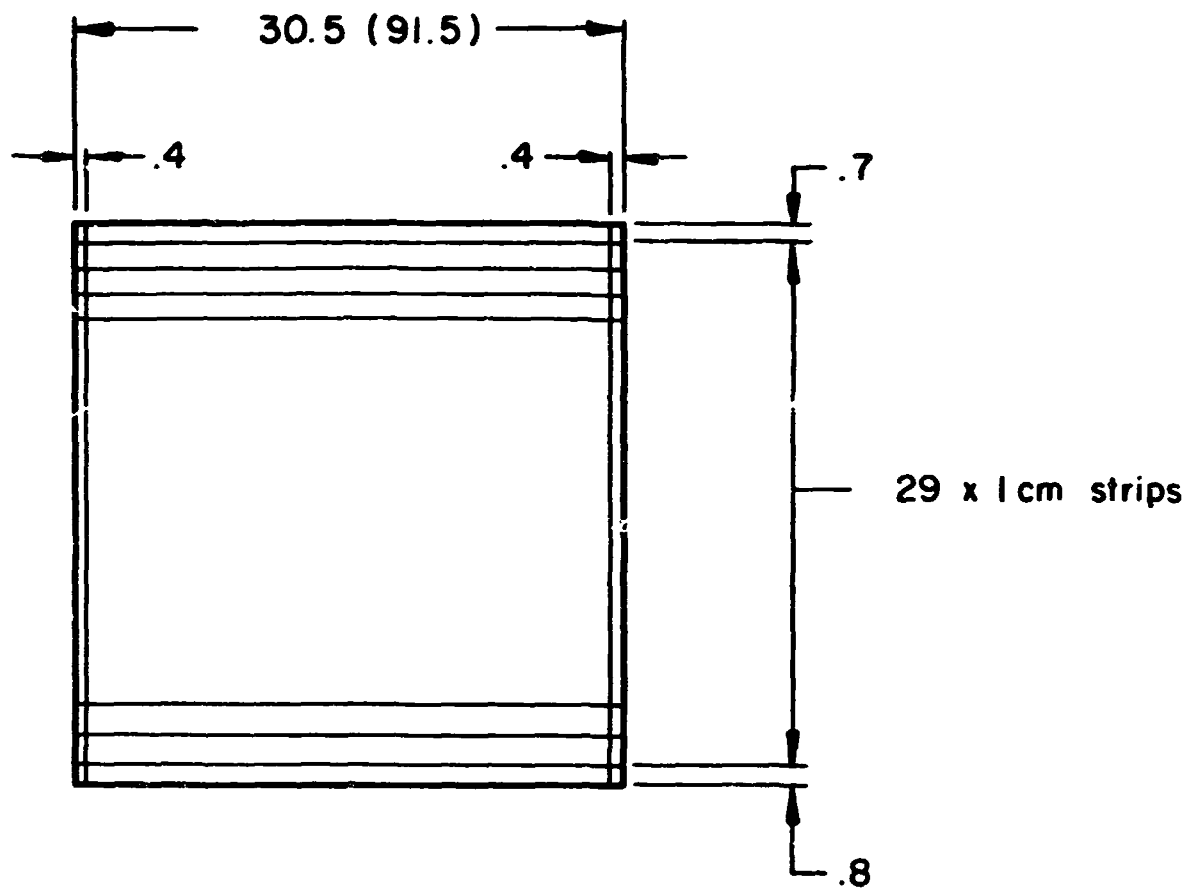
$$Rceff = (Rsh\,\rho c)\ \coth\{w(\frac{Rsh}{\rho c})1/2\}$$

From a plot of this equation, shown in Figure 6, it can be seen that for specific contact resistivities of 10^{-3} cm2 or less, little can be gained by increased contact widths beyond 0.01cm; that is Rceff is an acceptable 0.01 Ω for a 1cm long contact.

Experimental determination of Rceff and ρc under controlled conditions gave values for ρc of $10^{-4}\,\Omega$ cm2 for aluminum evaporated directly onto tin oxide. When aluminum was evaporated on tin oxide through a 0.01cm wide cut in silicon, somewhat higher values for ρc were obtained, $\sim 10^{-3}\,\Omega\,cm^2$

There are likely many factors that affect the magnitude of contact resistances. Three that are easily identified are the condition of the tin oxide surface, the quality of the cut in the silicon and the conditions prevailing during the metalization. We have found, not unexpectedly, that dirty tin oxide results in poor contacts. Not quite as obvious was the observation that when the silicon was laser cut from the silicon side (silicon facing the laser) poorer contacts were obtained on the average than when the glass faced the laser. The reason for this is that reflections from the silicon side are significantly greater than from the glass side and because of slight thickness variations in the films, reflections are variable; See Figure 6. Thus it is more difficult to achieve constant laser power levels at the Si when cutting the silicon with the silicon side up. The third factor that we looked at was the metalization step. Here we found that evaporating aluminum at high pressures, e.g. 10^{-4} torr, produces generally poor contacts. The cleanliness of the metalization chamber also seems to play an important role in the quality of the contact.

While the above discussion shows that poor contacts can be obtained, they can also be avoided by proper processing procedures. On our large PV panels, the contact resistances are generally too small to measure by the method discussed above, i.e. they are less than $\sim 0.05\Omega$. Extrapolation the values obtained on smaller 4" X 12" diagnostic panels where more sensitive techniques can be used suggests that contact resistances for large panels are in the low $m\Omega$ range. Thus they cause negligible degradation in panel performance. This conclusion is supported by the fact that 70+% fill factors have been measured for many individual interconnected cells and values near 70% for square foot panels.



	1' X 1'	1' X 3'
Total area :	929 cm^2	2787 cm^2
Active area :	792 cm^2 (85%)	2421 cm^2 (87%)

Figure 1 - Series connected cell patterns on 12" X 12" (or 12" X 36") panels.

Note: all measurements in cm

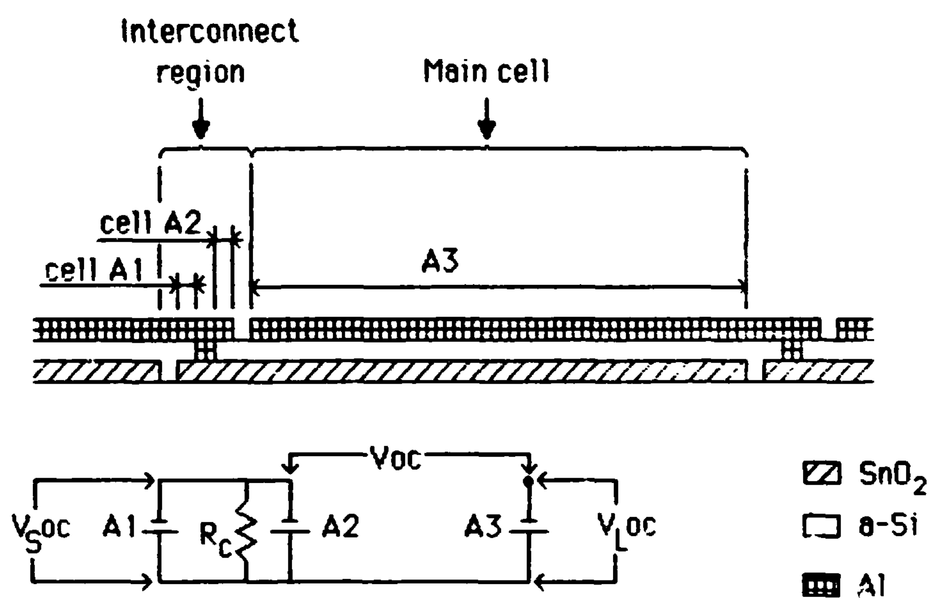


Fig. 2 Schematic presentation of the cross-section of a monolithic submodule showing a cell and the two adjacent interconnect regions.

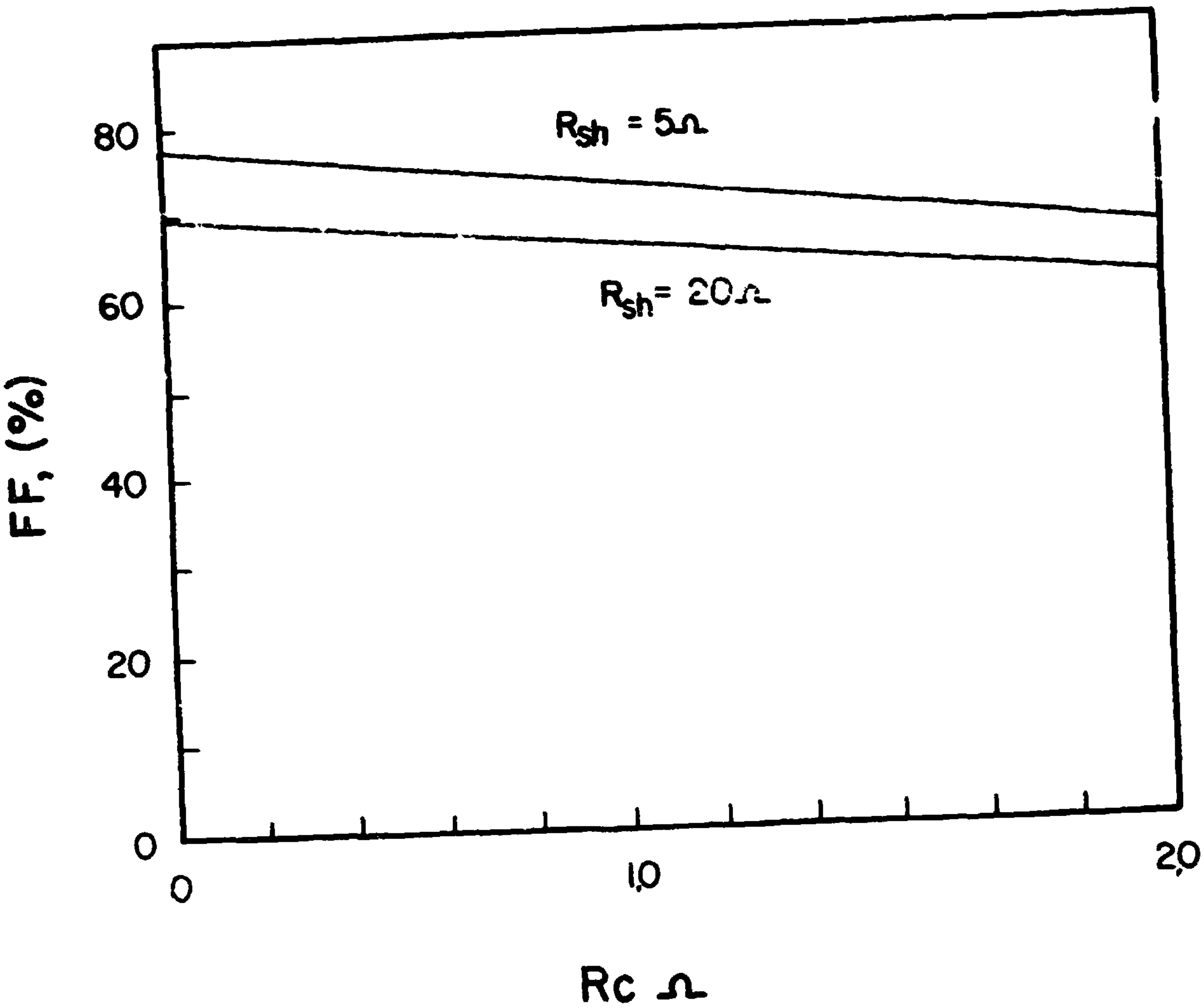


Figure 3 - Calculated dependence of FF on contact resistance R_c ; R_{sh} = SnO_2 sheet resistance.

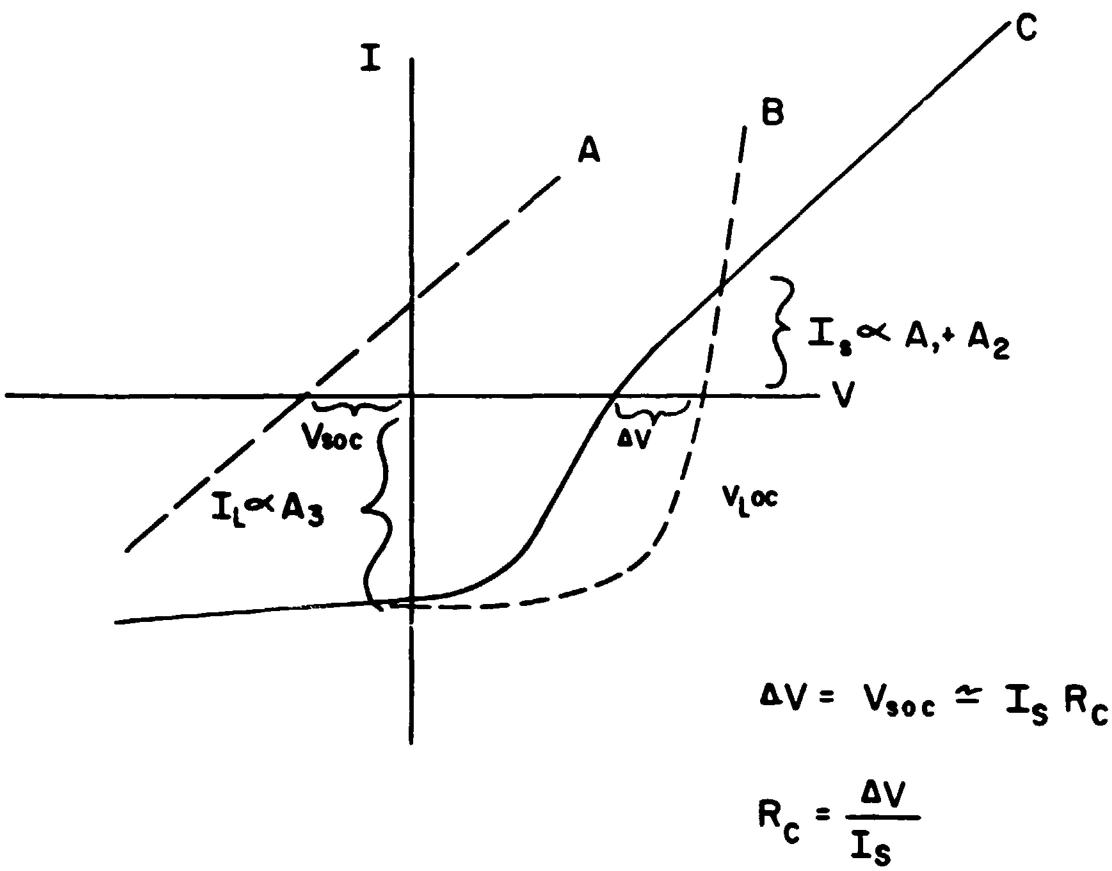
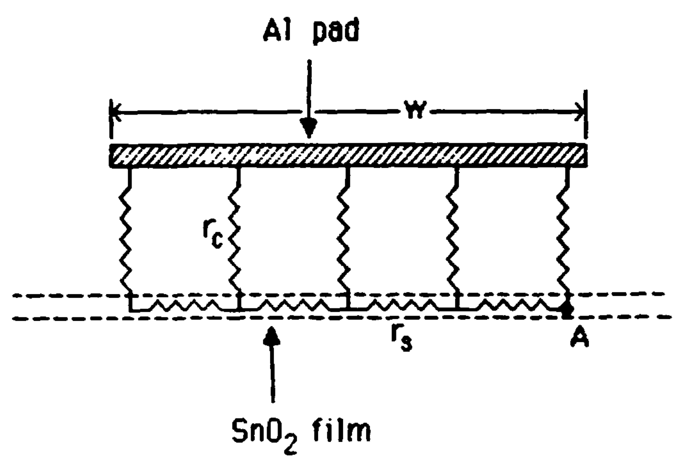


Figure 4 - Effect of the parasitic cells on the I-V characteristics of monoliticaly interconnected a-Si solar cell. See text for explanation.



$$r_s = \frac{R_{sh}\,dx}{W}$$

$$\frac{1}{r_c} = \frac{dx}{\rho_c}$$

Fig. 5 –Equivalent circuit model of Al / SnO_2 contact.

R_{sh} : sheet resistance of SnO_2 film.

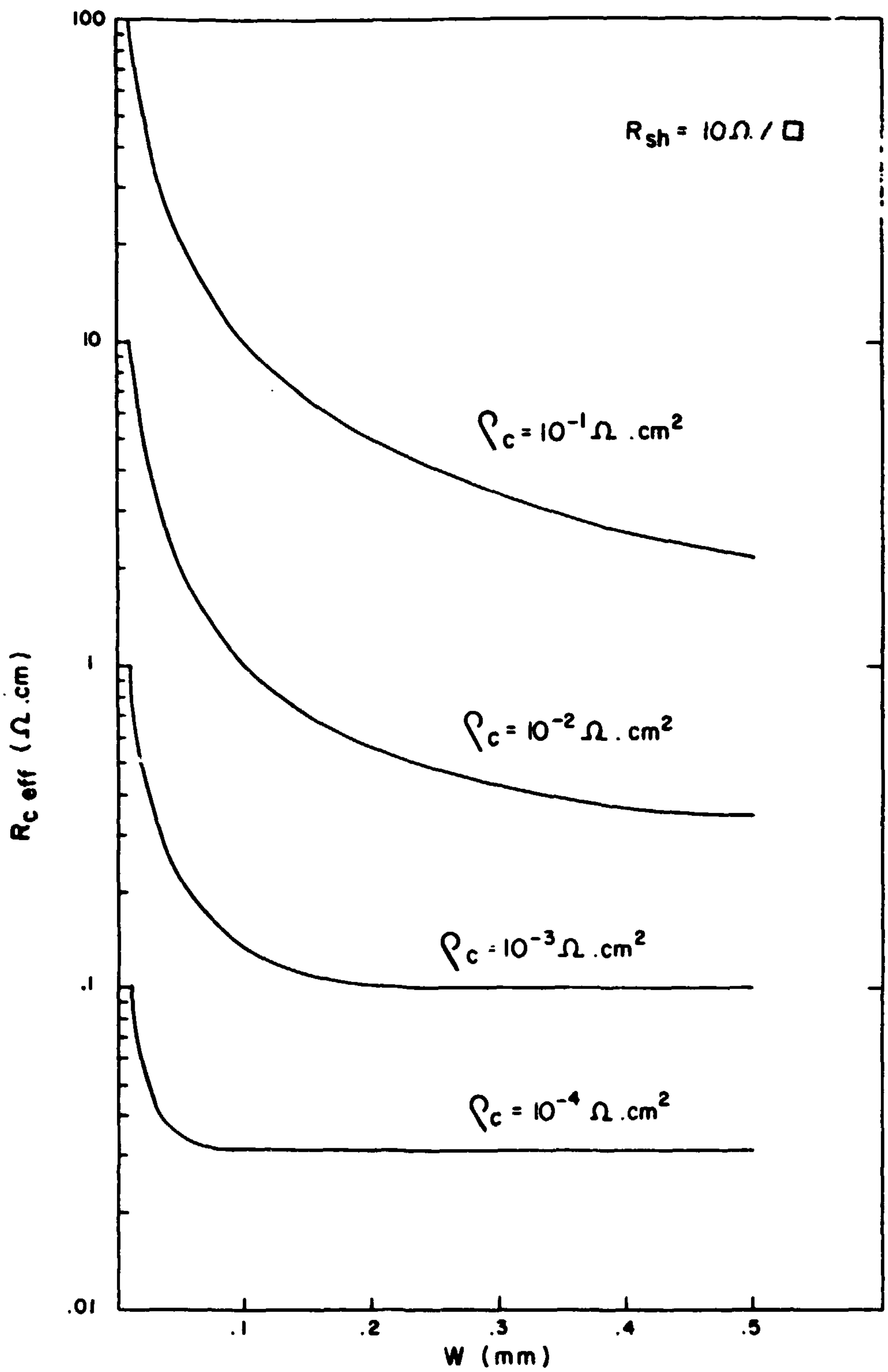


Figure 6 - Dependence of the effective Al / SnO_2 contact resistance on the contact width R_{sh}:sheet resistance of SnO_2 film; :specific contact resistivity.

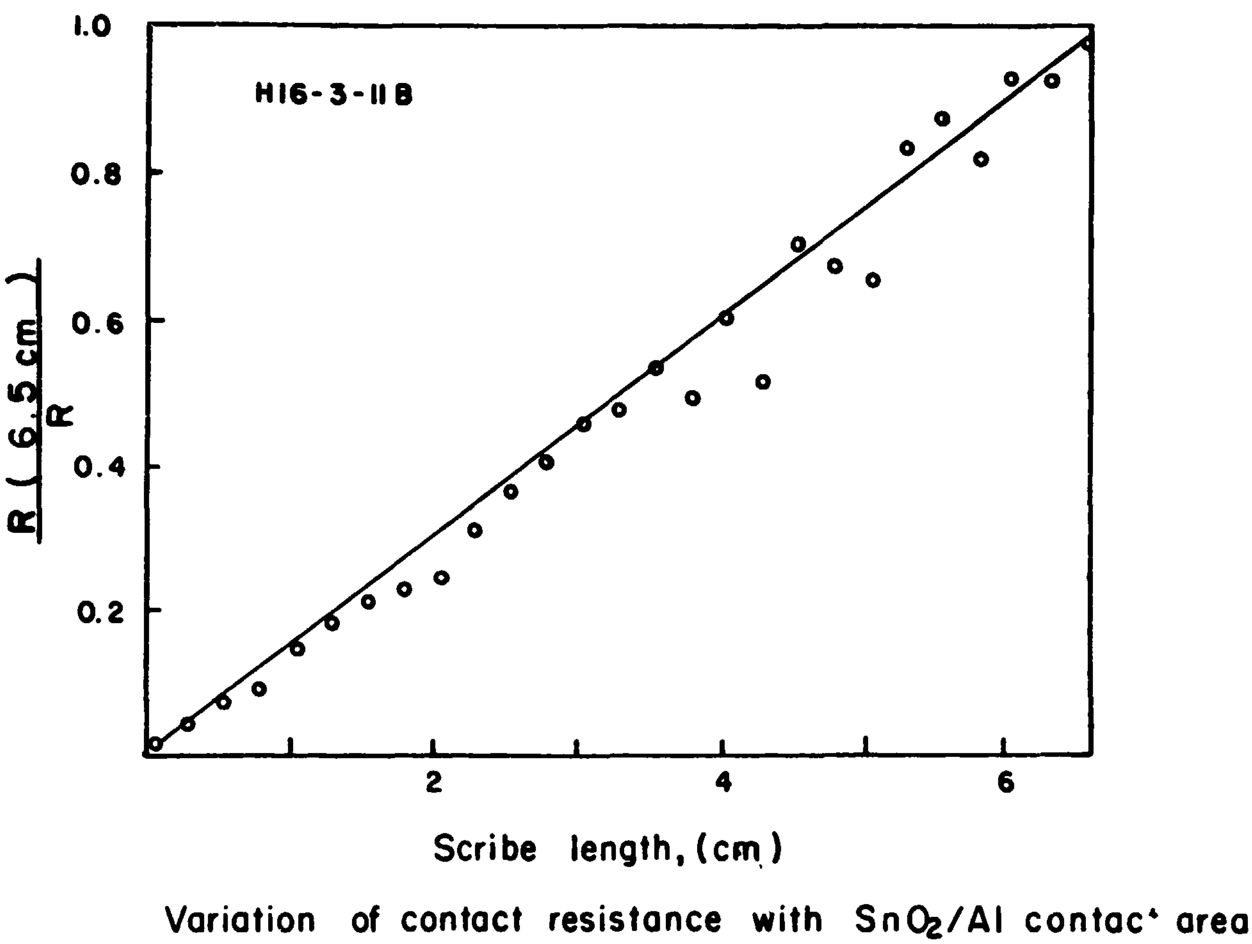


Figure 7 - Normalized inverse Al / SnO_2 contact resistance as a function of laser scribed contact length. Scribe width = 0.01cm.

DISCUSSION

LESK: When you do your laser cutting through the alpha silicon down to the tin oxide, ITO, if you don't go far enough you will leave a little bit of amorphous material, and it'll be of very high contact resistance. I presume you have to go a little too far. What is the accuracy of cutting into the tin oxide, since it is so thin? If you go all the way through, your contact on the edge of the ITO -- which is very bad -- these are practical problems that have to be solved.

VOLLTRAUER: These are practical problems, right. That's why having conditions where the power is controlled -- the power going into the films is controlled -- is important. There are a few other things we have done; one, for instance, is to make two laser cuts. Either the first one at a higher power level, where you might do some damage to the tin oxide but are assured of cutting all the silicon, and the other one displaced by a fraction of a scribe where you reduce the power to the point where you are assured of not cutting the tin oxide and you very likely will cut the silicon. That has worked out very well.