INTERCELL OHMIC CONTACTS FOR HIGH EFFICIENCY MULTIJUNCTION SOLAR CONVERTERS*

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SUMMARY

The monolithic multijunction converter is an attractive approach to achieving solar/electric conversion with greater than 30% efficiency. A major technical challenge in the development of such devices is the requirement for low resistance, optically transparent intercell contacts between adjacent junctions. These contacts should transmit, without significant loss, the spectral fraction of the incident sunlight which is not absorbed and converted in the overlying junction materials. Their contact resistances must be low enough to prevent significant I^2R loss at the designed current density levels. They should also exhibit adequate thermal conductivity to prevent device overheating when subjected to the designed illumination level.

Recent encouraging results for the development of such contacts are presented.

INTRODUCTION

The realization of high efficiency, monolithic multijunction solar converters is critically dependent on minimizing performance losses caused by their intercell ohmic contacts (IOC). This involves reducing the major sources of thermal and electrical resistance while maximizing optical transparency for the solar spectral fraction transmitted to the underlying, power-producing junctions.

In this paper we consider the types of losses expected from a tunnel junction IOC formed in GaAs. In our example, the IOC serves to transmit the optical, electrical and thermal flux passing from a well-optimized GaAs solar cell to an underlying cell having a bandgap of 0.7eV. The overall structure is shown schematically in Fig. 1.

The calculated performance parameters of such a converter excluding any IOC losses are summarized in Fig. 2 for operation at 300°K under 1 and 1000 SUNs AMO. For these calculations a conventional lumped circuit element model[1] is used for each cell, and it is assumed that the GaAs cell has an ideal diode factor n=1 and a dark saturation current density, $J_o=10^{-18}$amp/cm^2. The 0.7eV device is assumed to have n=1.7 and $J_o=10^{-4}$amp/cm^2 for operation at 1 SUN, and n=1, $J_o=10^{-7}$amp/cm^2 for 1000 SUNs operation. The values for the 0.7eV cell are representative of those measured in our laboratory for experimental GaSb

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devices[2]. Other performance losses due to reflection, front surface contact shadowing and less than perfect carrier collection have been ignored in these calculations, although a modest level ($.005\,\Omega$) of series resistance is included.

We proceed by considering the questions: 1) what are the specific types of losses to be expected for a tunnel homojunction IOC? 2) which of these are likely to be of major concern in a practical device? 3) what are the allowable magnitudes of critical IOC design parameters which can maintain each type of loss below an arbitrary limit of 1% of the initially calculated peak output power?

We later list some of the potential advantages of fabricating tunnel junction IOC's by molecular beam epitaxy (MBE), and report the electrical behavior of some experimental MBE tunnel junction structures fabricated in our laboratory.

SOURCES OF LOSS IN TUNNEL JUNCTION IOCs

The major electrical losses are controlled by the effective contact resistance of the IOC. The optical losses are determined by the degree of absorption and reflection of photons having energies in the bandwidth 1.42 to 0.7eV. The thermal loss contributions, if any, arise from possible temperature increases in the upper cell due to I^2R losses in the IOC and to any increase in thermal resistance due to its presence.

Electrical Losses

For a cm^2 of IOC area, the ohmic power loss is given by $J_m^2R_c$ where J_m is the current density (amp/cm^2) at peak output power and R_c is the effective contact resistance (Ωcm^2) of the IOC. Thus at 1 SUN for $J_m^2R_c \leqslant .01P_m$ (the 1% loss criterion):

$$R_c \leqslant \frac{1}{(29 \times 10^{-3})^2} \cdot (.01)(30.96 \times 10^{-3}) = .368\,\Omega\text{cm}^2 .$$

The equivalent value for 1000 SUN operation is $4.8 \times 10^{-4}\,\Omega$cm . The resulting heat loads are 3.1×10^{-4} W/cm^2 and .46 W/cm^2 respectively for 1 SUN and 1000 SUNs and the corresponding voltage drops across the IOC are 10.7 mV and 14.6 mV.

The I^2R heating thus developed in the IOC adds to the heat load which must be effectively dissipated to maintain a low converter operating temperature. For typical semiconductors with thermal conductance in the range of several tenths of a watt/°K cm, and thicknesses of the order of several hundredths of a cm, even a 10% ohmic IOC loss at 1000 SUN operation contributes less than 1°C to the temperature difference between the upper and lower cells. This upper bound can be estimated using the relation:

$$\Delta T = \frac{J_m^2 R\, l}{kA}$$

where ΔT = temperature difference of the boundaries of a layer of thickness l, area A, and thermal conductivity k due to a source of steady heat flux of strength J^2R located at the higher temperature surface of the layer.

Optical Losses

Interface Reflection

If the IOC is designed such that there is an interface between materials having different refractive indices, there will be reflection losses. The magnitude of these losses will, in general, vary slightly with wavelength since refractive indices are usually weak functions of wavelength. A review of refractive index values measured for III-V compounds with bandgaps of interest for multijunction solar cell applications shows that they all lie in the range of ~3.4 to ~4.1 . Over this limited range, even without the use of anti-reflection design principles, involving optimally dimensional thin layers, these differences lead to losses of $\leqslant 0.7\%$, according to the reflectivity relation:

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} .$$

Even for a heterojunction involving GaAs (n = 4.025) and Ge (n = 5.6), the reflection losses would be no more than ~3%.

Below Bandgap Absorption

Because of the high doping used in the formation of tunnel junctions, free carrier absorption of below bandgap photons can be an important potential loss mechanism. The magnitudes of these losses for n++and p++ GaAs doped to $10^{20}\,\mathrm{cm}^{-3}$ are indicated by the curves of Fig. 3a. These show the transmitted photon fraction as a function of layer thickness for 1.35eV and 0.7eV photons. As noted, to maintain at least 99% transmission of 0.7eV photons, the p++ layer must be no more than 160Å thick. The equivalent transmission thickness for a similarly doped n++ layer is shown to be ~1250Å. The thicknesses for 99% transmission of higher energy photons up to nearly bandgap energy can be significantly greater as indicated by the transmission vs. thickness curves for 1.35eV photons. The actual absorption vs. photon energy curve for p = $10^{20}\,\mathrm{cm}^{-3}$ GaAs is shown in Fig. 3b[4] along with an estimated curve for n = $10^{20}\,\mathrm{cm}^{-3}$ GaAs developed by extrapolating available literature data[5] for lower doped material.

As summarized in Fig. 4, the above considerations suggest that the most critical source of performance loss in GaAs tunnel IOC's operating at high solar concentrations is expected to be that due to excessive contact resistance. Also indicated is a need for careful thickness control of the heavily doped layers to maintain an acceptably low level of absorption loss for below bandgap photons.

There is evidence in the literature than tunnel IOC's having acceptable contact resistance for even 1000 SUN operation can be realized. Holonyak & Lesk[6] report alloyed GaAs tunnel diodes with peak current densities of 2000 - 10,000 amp/cm^2 coupled with peak voltages of 0.1 to 0.25 Volts. While it is not clear from their paper which peak voltage goes with which peak current density, even the most conservative combination implies an effective contact resistance of no more than $1.25 \times 10^{-4}\ \Omega\mathrm{cm}^2$ for these devices. This compares well with the $4.8 \times 10^{-4}\ \Omega\mathrm{cm}^2$ calculated as an upper limit for 1% I^2R loss under 1000 SUN AMO operation. Because of the non-transparency of these alloyed diodes, there is a need to demonstrate acceptably low contact resistance in tunneling structures formed by other methods.

PRELIMINARY RESULTS FOR GaAs TUNNEL JUNCTIONS FORMED BY MBE

A number of potential advantages of molecular beam epitaxy as a means of fabricating tunneling structures are listed in Fig. 5.

To begin to explore the behavior of such junctions, the structures shown schematically in Fig. 6 were fabricated. Be was used as the p++ dopant because of its relatively low diffusivity compared to Zn or Cd and because neither Zn or Cd are useable with MBE because of their high vapor pressure. The electrical characteristics of the structures were measured in the as-grown condition and after a subsequent heat treatment in which they were subjected to the same thermal history that they would experience if a high performance GaAs cell were later grown on them by LPE. The point of this additional heat treatment experiment was to note any changes in I-V characteristics which might result. The concern was that diffusion of dopants might degrade the performance of the original structures and make them unsuitable for use as IOCs.

The I-V curves obtained for the two structures before and after the indicated heat treatment are shown in Fig. 7. Their qualitative appearance indicates a tendency toward more ohmic behavior following heat treatment.

Semi-quantitative estimates of their upper bound specific contact resistance are presented in Fig. 8. These values were obtained using the multiple area contact method of Cox & Strack[7]. This technique is ordinarily used to measure the specific resistance of surface contact metallization, by separating it from all other sources of resistance in the test structure and measurement system. In the present case, the tunnel contact resistance is lumped with the surface contact resistance so that the measured result is at best an upper bound. Other experiments on just the surface contacts, without the tunnel structures, indicate that their contributions to the measured upper bound value for the complete structure is $<10\%$. The measured values are sufficiently low for use in 1 SUN devices. For concentrated illumination beyond ~20 SUNs, however, their I^2R losses would exceed the 1% loss criterion.

Based on tunnel junction theory[8], it is expected that with thinner layers and higher doping levels these structures can approach sufficiently close to the low contact resistances reported for alloyed devices to be useful for high concentration operation.

SUMMARY

Potential sources and levels of performance losses have been assessed for GaAs tunnel junction IOC's. Our conclusion is that only electrical losses due to excessive contact resistance and optical losses due to excessive free carrier absorption in the highly doped layers are of practical significance. There is reason to believe that both these types of loss can be maintained at acceptably low levels for good overall device performance.

Evaluation of preliminary GaAs tunnel junction structures formed by MBE indicate acceptable contact resistance values for 1 SUN operation but not for concentrator applications above ~20 SUNs. It is expected that with thinner layers and higher doping, sufficiently low resistances can be achieved to allow operation at high solar concentration (~1000 SUNs). It was found that the structures tested had sufficient thermal stability to allow subsequent LPE growth of a high performance GaAs window solar cell structure.

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A TWO BANDGAP SOLAR CELL

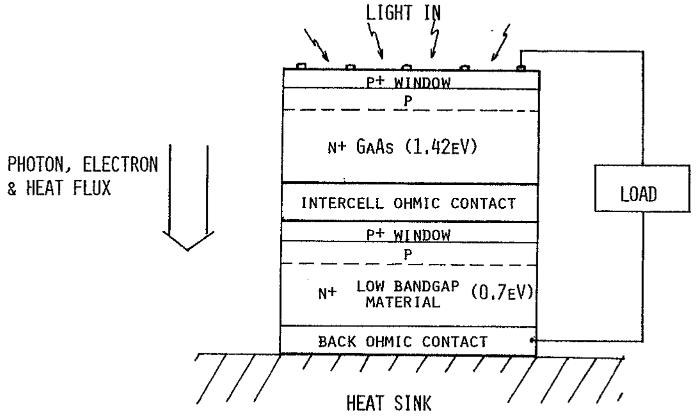


Figure 1

PERFORMANCE PARAMETERS FOR A TWO-BANDGAP SOLAR CELL*

INSOLATION	1 SUN, AMO (.135W/CM^2)	1000 SUN, AMO (135W/CM^2)
TOP CELL (1.42eV)		
J_{SC} (AMP/CM^2)	32×10^{-3}	32
V_{OC} (VOLT)	.943	1.12
P_M	26.4×10^{-3}	32.01
BOTTOM CELL (0.7eV)		
J_{SC} (AMP/CM^2)	34×10^{-3}	34
V_{OC} (VOLT)	0.26	0.56
P_M	5.06×10^{-3}	14.06
TOTAL DEVICE		
J_M (AMP/CM^2)	29×10^{-3}	31.1
V_M (VOLT)	1.067	1.48
P_M	30.96×10^{-3}	46.1
FF	.793	.84
η (%)	22.9	34.1
I^2R_S LOSS (%)	.013	10.5

*TOTAL SERIES RESISTANCE, $\boxed{R_S = .005\Omega/\text{CM}^2}$ 300°K OPERATING TEMPERATURE.

Figure 2

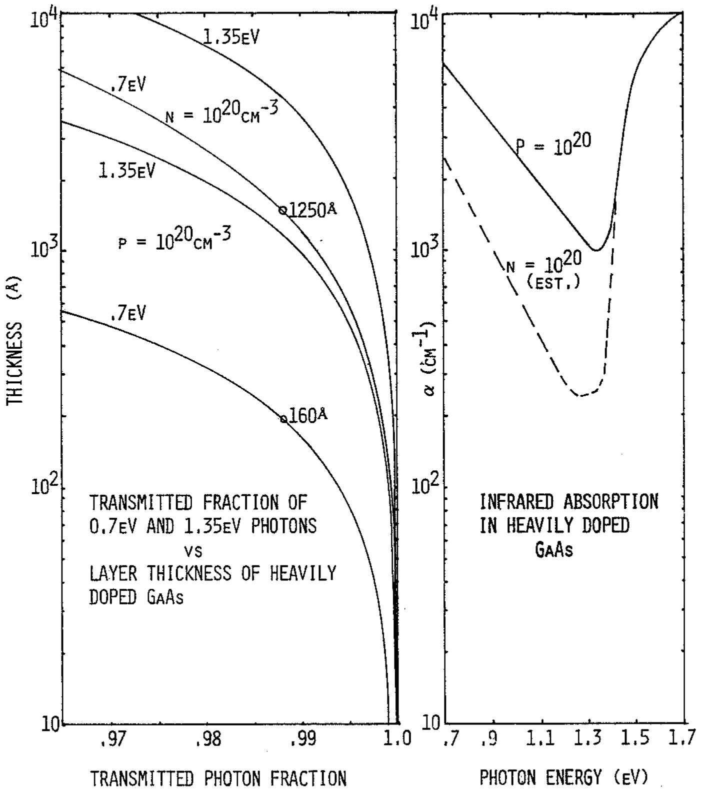


Figure 3

PARAMETERS FOR 1% LOSSES AT INTERCELL OHMIC CONTACT

	1 SUN, AMO	1000 SUN, AMO
ELECTRICAL		
CONTACT RESISTANCE, R_C:	<.37 OHM-CM^2	<4.8 x 10^{-4} Ω-CM^2
OPTICAL		
ABSORPTION IN HEAVILY DOPED (10^{20}) LAYERS, THICKNESS:	P++ GaAs, T ≲ 160Å N++ GaAs, T ≲ 1250Å	
REFLECTION AT INTERFACE:	LOSS IS <1% FOR MOST III-V HETEROJUNCTIONS*	
THERMAL		
LOSS OF OUTPUT DUE TO UPPER CELL HEATING:	NO PROBLEM	NO PROBLEM

* FOR GaAs/Ge, INTERFACIAL REFLECTION LOSS IS 2.7%

Figure 4

POTENTIAL ADVANTAGES OF MBE FOR INTERCELL OHMIC JUNCTIONS

- LOW GROWTH TEMPERATURES (~400-550°C FOR GaAs)
- EXCELLENT THICKNESS CONTROL IN THE 100Å-1000Å RANGE
- EXPANDED CHOICE OF DOPING SPECIES, CONCENTRATIONS AND PROFILES
- REALIZATION OF VERY ABRUPT JUNCTION TRANSITIONS

Figure 5

MBE OHMIC JUNCTIONS IN GaAs

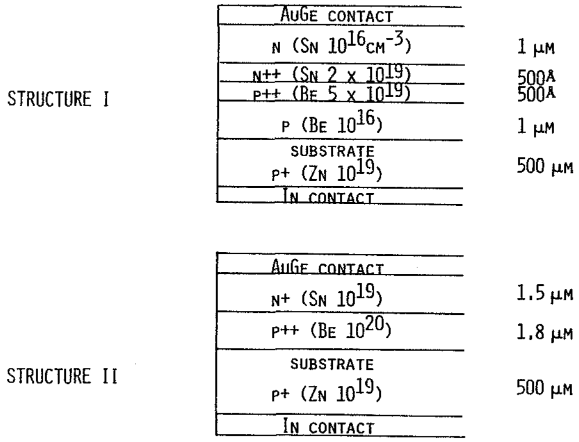
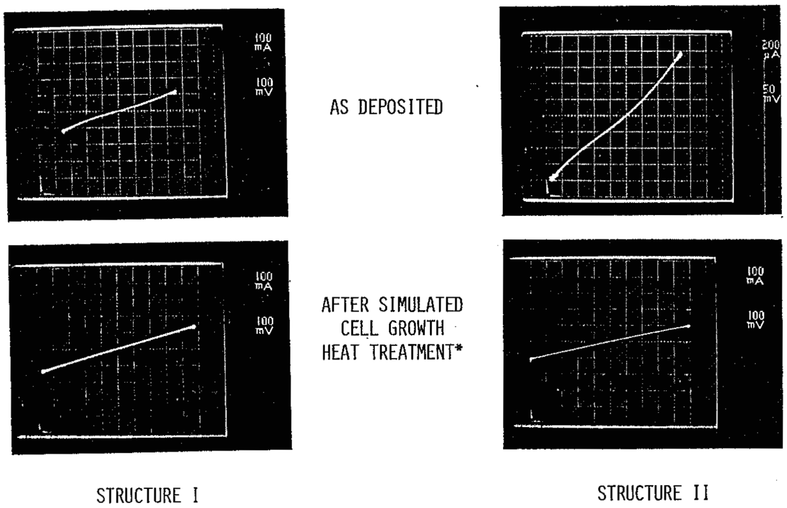


Figure 6

TYPICAL I-V CURVES FOR MBE INTERCELL OHMIC CONTACTS



* HEAT R.T. TO 745°C
HOLD 1/2 HR @ 745°C
COOL 10°C @ 1°C/MIN
FURNACE COOL TO R.T.

Figure 7

ESTIMATED CONTACT RESISTANCE FOR MBE OHMIC CONTACTS

	AS GROWN	AFTER HEAT TREATMENT
STRUCTURE I (500Å LAYERS)	$<.03\,\Omega\text{cm}^2$	$<.025\,\Omega\text{cm}^2$
STRUCTURE II (1-2µM LAYERS)	$<.04\,\Omega\text{cm}^2$	$<.07\,\Omega\text{cm}^2$

1% LOSS AT ~10-15 SUNS, AMO

NEED ~$5 \times 10^{-4}\,\Omega\text{cm}^2$ FOR 1% LOSS AT 1000 SUNS, AMO

Figure 8