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Tandem Concentrator Solar Cells with 30% (AM0) Power Conversion Efficiency

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Introduction

Very high efficiency concentrator solar panels are envisioned as economical and reliable electrical power subsystems for space based platforms of the future. Single junction GaAs solar cell efficiencies as high as 25% have been reported at concentrated light levels of 300 suns AM0 [ref. 1]. However, this material precludes the collection of about 40% of the solar energy spectrum below the GaAs bandgap energy of 1.42 eV since this energy cannot be absorbed by the GaAs. Enhanced efficiencies may be realized by stacking GaAs either monolithically or mechanically on top of such lower bandgap materials as Ge, Si, CIS or InGaAs which do convert at least some portion of the longer wavelength light [refs. 2-5].

Gallium Antimonide (GaSb) was selected as a preferred low bandgap candidate material [ref. 6] because it has an appropriate bandgap energy of 0.72 eV and is a direct gap material with a high absorption coefficient. It is a binary compound that can be formed into high quality single crystal ingots using the liquid-encapsulated Czochralski technique (LEC) and then shaped, wafered and polished. Solar cell junctions can be diffused into GaSb so wafers can be processed directly without any epi growth. With all of these desirable features GaSb cells are likely to reach theoretical performance limits.

Mechanical stacking permits independent processing of the two wafer materials allowing process variables like temperature to be optimized for a lesser set of materials interfaces [ref. 7]. Also, separate stacked cells can be interconnected in a voltage matched configuration to achieve 2 terminal operation.

Entech solar cell covers [ref. 8] were applied to both the GaAs and GaSb cells to enhance the collected current and efficiency. These covers have molded optical elements that divert incoming light away from obscuring grid lines onto active cell area.

Transparent GaAs and GaSb Booster Cell Development

Both types of cells are processed at the wafer level starting with single crystal wafers and using fairly conventional equipment and procedures. Dozens of individual concentrator cell dies are then scribed out of each wafer. Figure 1 shows a processed wafer and a waffle pack of dies ready for assembly, along with a mounted die and a finished test article which are described later.

The GaAs active layers are deposited by MOCVD epi growth. Subsequent steps include patterned metallizations, cap etching and AR coating. Transparent GaAs cells for tandem stacks differ from their single junction counterparts in several ways. The back metal must be opened to let sub-bandgap radiation pass through. Back surface gridlines are not necessary for small cells which have low back surface sheet resistance. The doping level of the bulk wafer is selected to minimize absorption below the bandedge of the GaAs, without increasing series resistance loss through the wafer or at the back contact interface. Good results are obtained in the $1-3 \times 10^{17}$ range for N-type substrates. Absorption losses for standard wafer thicknesses of 450 microns are normally less than 10% in the range of interest, from the bandedge of the GaAs at 0.9 microns to the bandedge of GaSb at 1.72 microns. Further reductions in absorption loss would be gained by thinning the wafer or using less bulk doping. However, the electrical performance or mechanical yield might suffer.

The transparent GaAs cell is AR coated on both the front and back surface to maximize the transmission of long wavelength energy through to the GaSb booster cell. Figure 2 shows schematically a GaAs filter that consists of a GaAs wafer with solar cell epi layers and front and back surface multilayer AR coatings. The figure also shows measured transmission and reflectance characteristics of the real filter. Note the broadband peak transmission rising from the GaAs bandedge to 95%, and the very low total reflectance over the entire solar spectral range.

Figure 3 shows the IV performance curve of a transparent GaAs solar cell fabricated at Boeing and measured at NASA/Lewis. The 23.8% efficiency of this transparent GaAs cell compares very favorably with the best non-transparent cell values measured in the same lab, and is equivalent to non-transparent cells from the same Boeing epi run.

GaSb cell processing [ref. 9] is accomplished using conventional semiconductor processing equipment and procedures. After applying a nitride diffusion mask , a planar patterned emitter is formed by zinc diffusion in an open tube. The back surface is fully metallized. Patterned front metal is deposited using standard lift-off techniques. Only gridlines touch the semiconductor surface. Bonding pads are on top of the dielectric layer away from the junction.The junction is etched back and

AR coated to maximize photocurrent, while leaving a deeper junction under the grid metal. This configuration helps to prevent shunting of the junction during bonding and assembly.

The very first GaSb solar cells were over 5% efficient behind a GaAs filter. Table 1 shows this filtered efficiency increasing with time to a recent high value of 8.7%. Further increases are expected. The improvements in current, voltage and fill factor shown in the table are the result of basic improvements in specific recipes for each process step. Also, with better cells the efficiency peak versus intensity moves out to higher light levels as the voltage and fill factor continue to climb. As with GaAs, the currents and efficiencies of GaSb cells increase over 10% with Entech covers. Notice how "covered" efficiencies in the table track the baseline filtered measurements. Stacked efficiencies, measured behind a transparent GaAs cell, will also follow the upward trend.

Figure 4 shows the IV characteristics of a covered and filtered GaSb cell from the Sep-89 group of table 1, measured at Sandia on a pulsed xenon lamp simulator using a NASA flown GaAs AM0 reference standard. The voltage, fill factor and current are consistent with Boeing measured values.

Mechanically Stacked GaAs/GaSb Test Article Assembly

Figure 5 illustrates how one front cell and one back cell are assembled together into a test article for illuminated performance testing. Cells are first bonded to thin metal disks with silver epoxy. The disks have center holes slightly larger than the cell active areas so that light can pass through. Entech covers are applied to both cells at this point. Front and back disks are then positioned as shown in the figure and clamped between insulators and terminals to the heat sink. The locator provides for alignment of the disks. The back contact of the back cell is either pressed against the block or wire bonded to the bottom terminal. The front contact of the back cell and the back contact of the front cell share a common terminal pressed against both disks. The front contact of the front cell is preferably wire bonded to the top terminal, otherwise this contact can be probed. In this configuration each of the stacked cells is tested individually and an added total efficiency is reported.

The metal disks provide for heat spreading from the cells through the conductive epoxy, distributing excess thermal energy over a larger area path to the block. This particular configuration, when held by vacuum to a temperature controlled chuck, holds the junction temperature of both cells to within a few degrees of the chuck during testing with light beam intensities on the cells up to 200 suns.

The test articles described above are useful for monitoring cell performance during process development and for verification testing between labs. However, they do not allow for testing both cells together in a 2 terminal configuration because the maximum power currents and voltages of the different bandgap cells are not matched.

In fact typical max power voltages for the GaSb cells are about 1/3 of the GaAs. 3 to 1 voltage matched circuits have been fabricated and tested [ref. 10] using double sided printed circuit boards. 2 terminal operation has been demonstrated up to a 3x3 matrix level with a total efficiency equal to the sum of the front and back circuits measured separately.

Concentrated Light Performance Testing

Figure 6 shows the concentrated light IV test station constructed and used at Boeing to measure front and back cells during processing and after assembly. The station provides up to 200 suns AM0. A standard wafer prober allows for automatic step and repeat testing at the wafer level. The one inch beam from a 300 watt xenon spotlight is focused through microscope optics onto a temperature controlled test plane. Selectable objective lenses and adjustable irises in the optical path provide for a continuous range of light levels up to the 200x maximum. At the highest light level with a 10x final objective, the beam size is about 3 millimeter diameter with a power density of 25 watts/cm^2. An electronic shutter in the lamp housing is synchronized with the testing to prevent overheating the optics.

I-V data pairs are collected by the control computer and reduced to summary values. The cycle time per cell test is 500 milliseconds. During the test cycle good thermal contact to the chuck holds the cells near a standard block temperature of 25 degrees C.

At NASA and Sandia, assembled cells were tested on pulsed-xenon flashlamp simulators using fresnel lenses to concentrate the light. Very short pulse times minimize thermal loading of the test structure for constant temperature measurements. These simulators are also capable of producing high test-beam intensities and may be suitable for testing larger area samples and minimodules with multiple lenses.

Boeing, Sandia and NASA share a common procedure for calibrating the concentrated light beam intensity using 1 sun reference standards and assuming a linear relationship between the I_{sc} of a solar cell and the beam intensity. This procedure is fairly well developed for GaAs, but since GaSb is a new solar cell material it will require additional calibration testing. Additional test articles are being assembled for upcoming NASA high altitude plane flight calibrations to the AM0 spectrum [ref. 11].

Table 2 presents the performance data summary of a mechanically stacked GaAs/GaSb tandem cell. It compares values measured at Boeing and NASA/Lewis. Note that combined efficiencies greater than 30% at light levels up to 100x AM0 were recorded at both locations. V_{oc}, FF, V_{max} and 1 sun current (I_{sc}/C_{onx}) values are all quite consistent. Recent improvements in GaSb cell performance are expected to raise the total efficiency by another 1 to 2 percentage points.

Conclusions

GaAs concentrator cells with very high efficiencies and good sub-bandgap transmissions can be fabricated on standard wafers. GaSb booster cell development is progressing very well; performance characteristics are still improving dramatically. Consistent GaAs/GaSb stacked cell AM0 efficiencies greater than 30% are expected.

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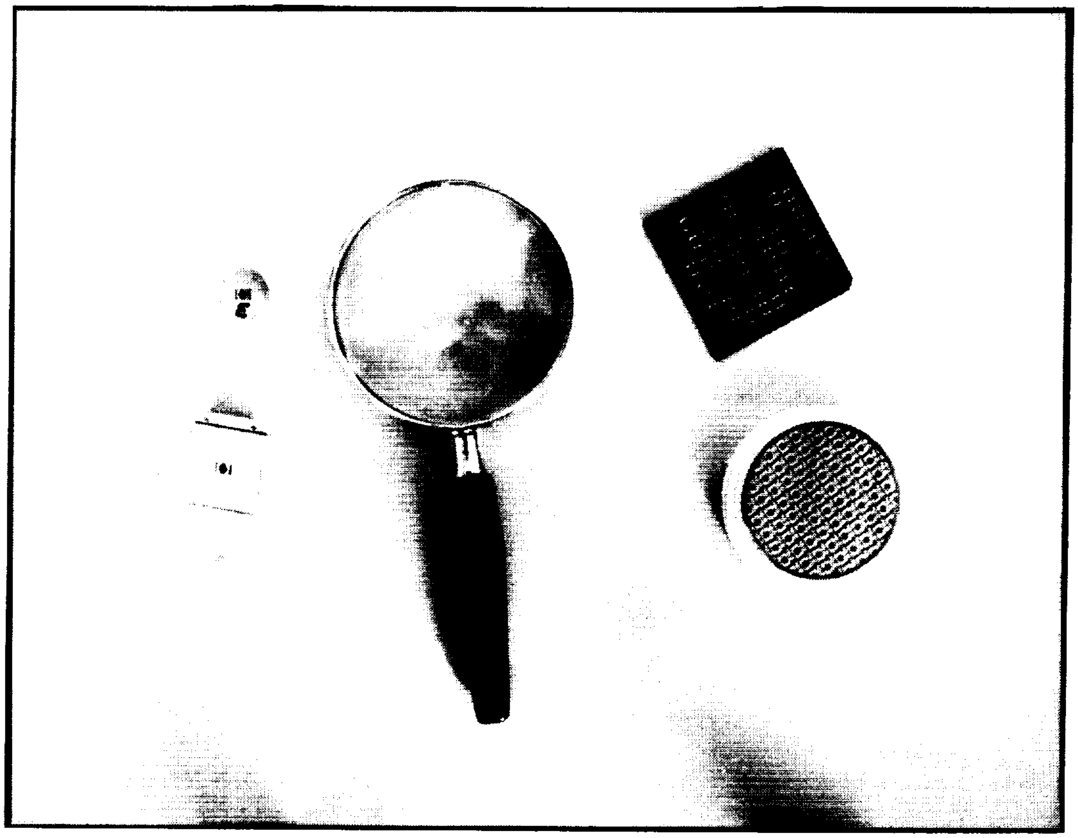
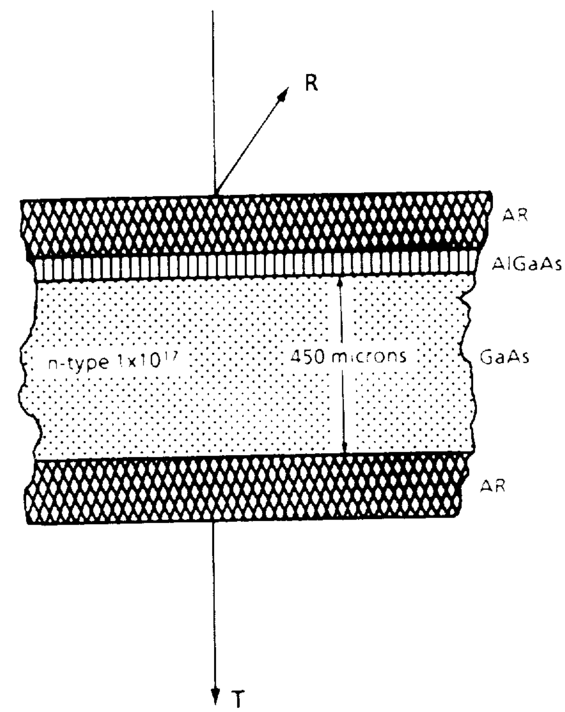


Figure 1. Boeing Processed Wafer, Diced Concentrator Cells and Mounted Concentrator Cells



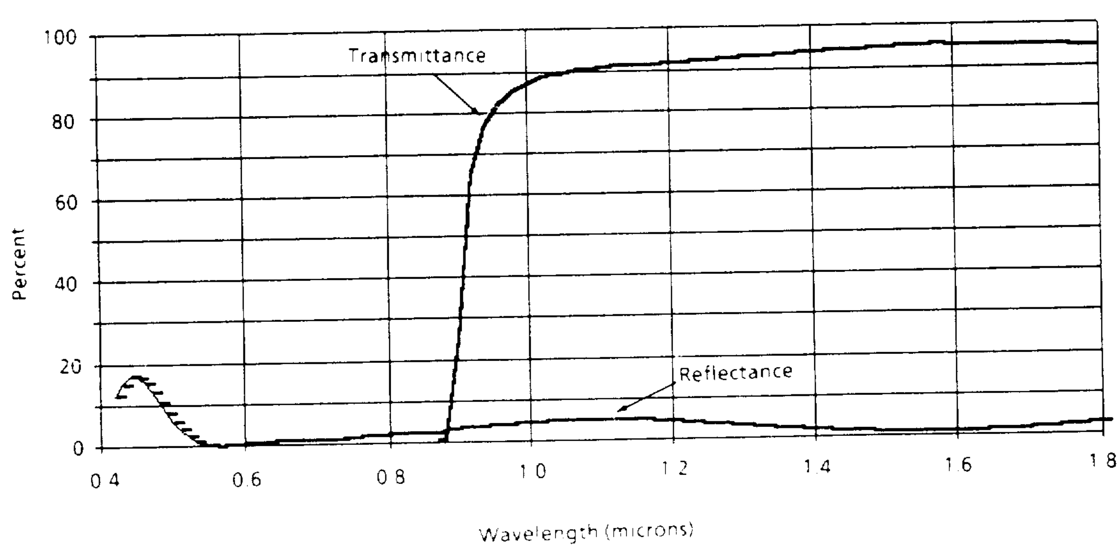


Figure 2. Transparent GaAs Filter

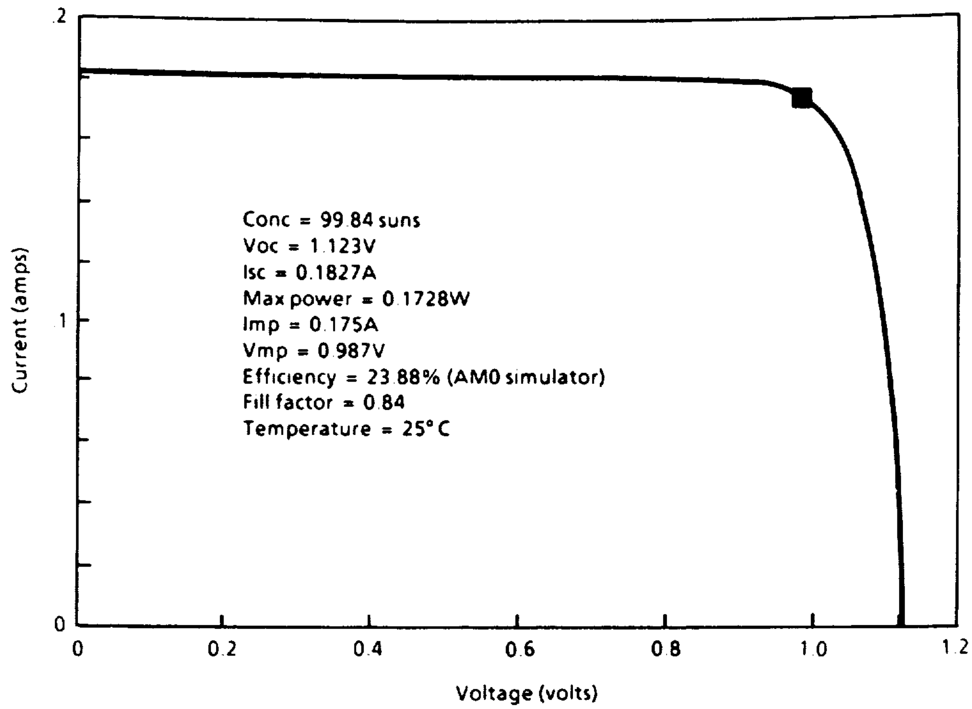


Figure 3. Boeing GaAs Cell, NASA Test AM0

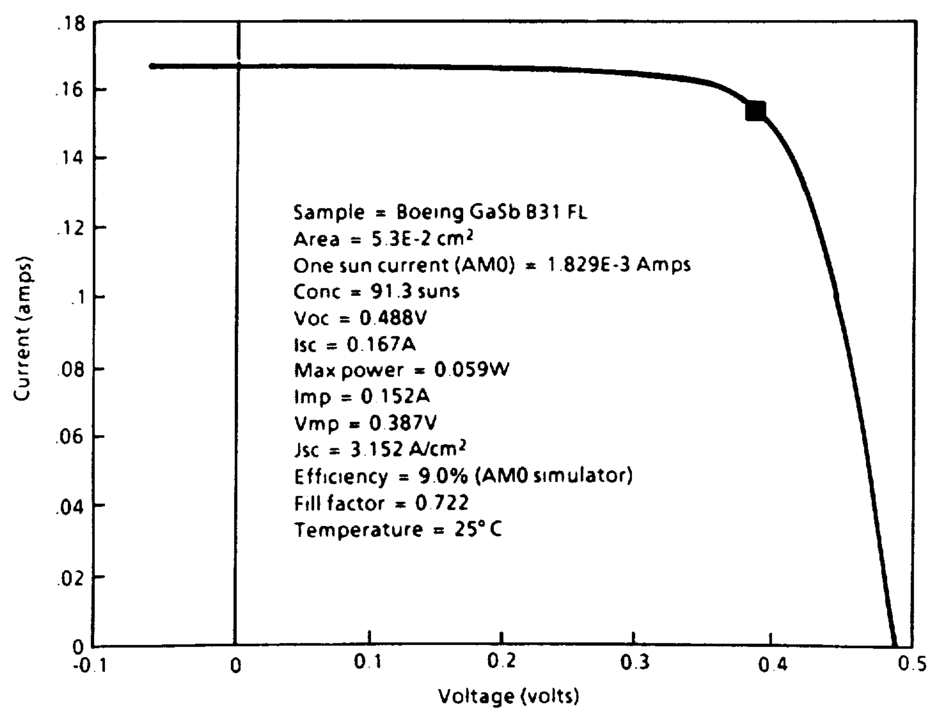


Figure 4. Boeing GaSb Cell, Sandia Test AM0

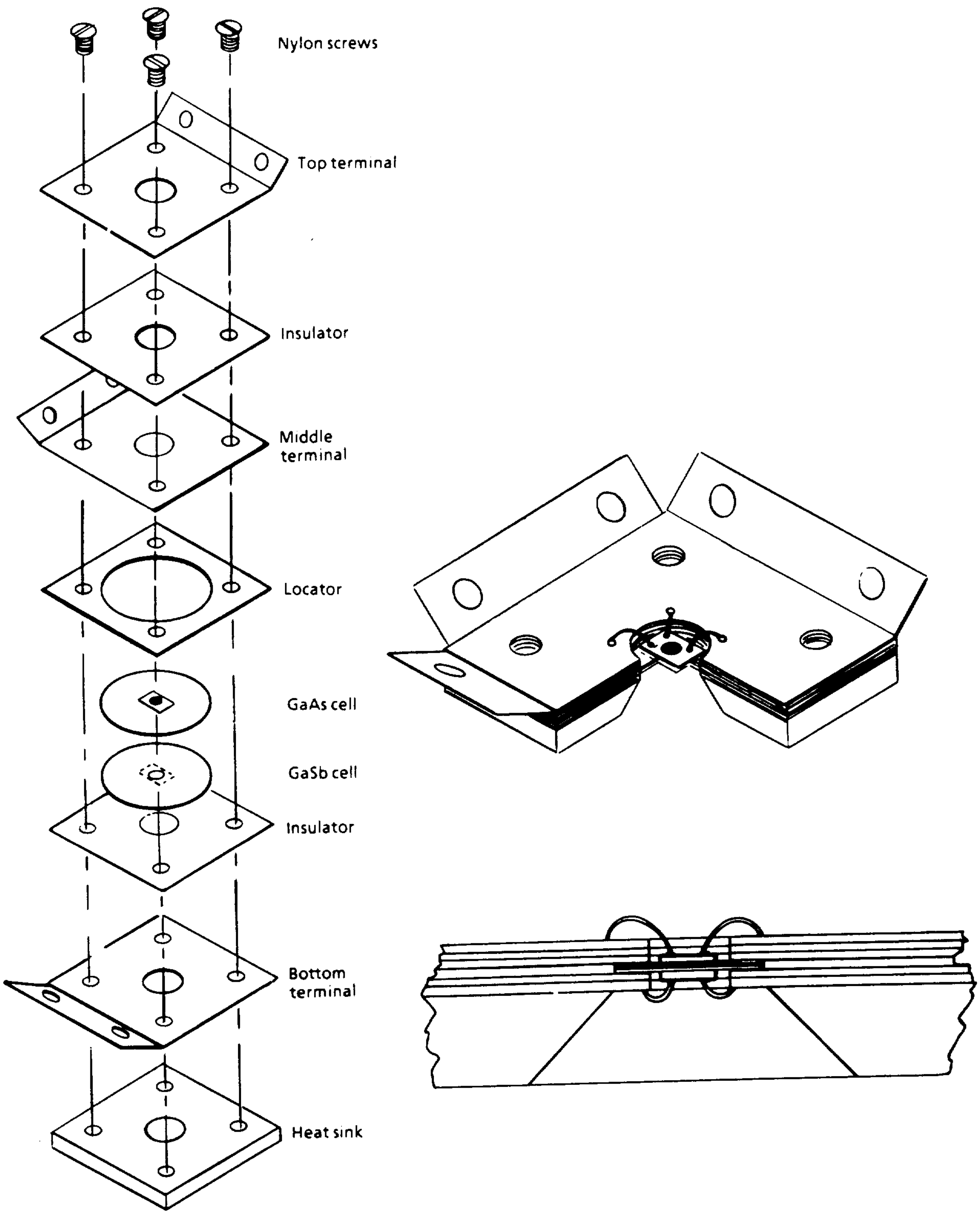


Figure 5. Tandem Cell Test Article

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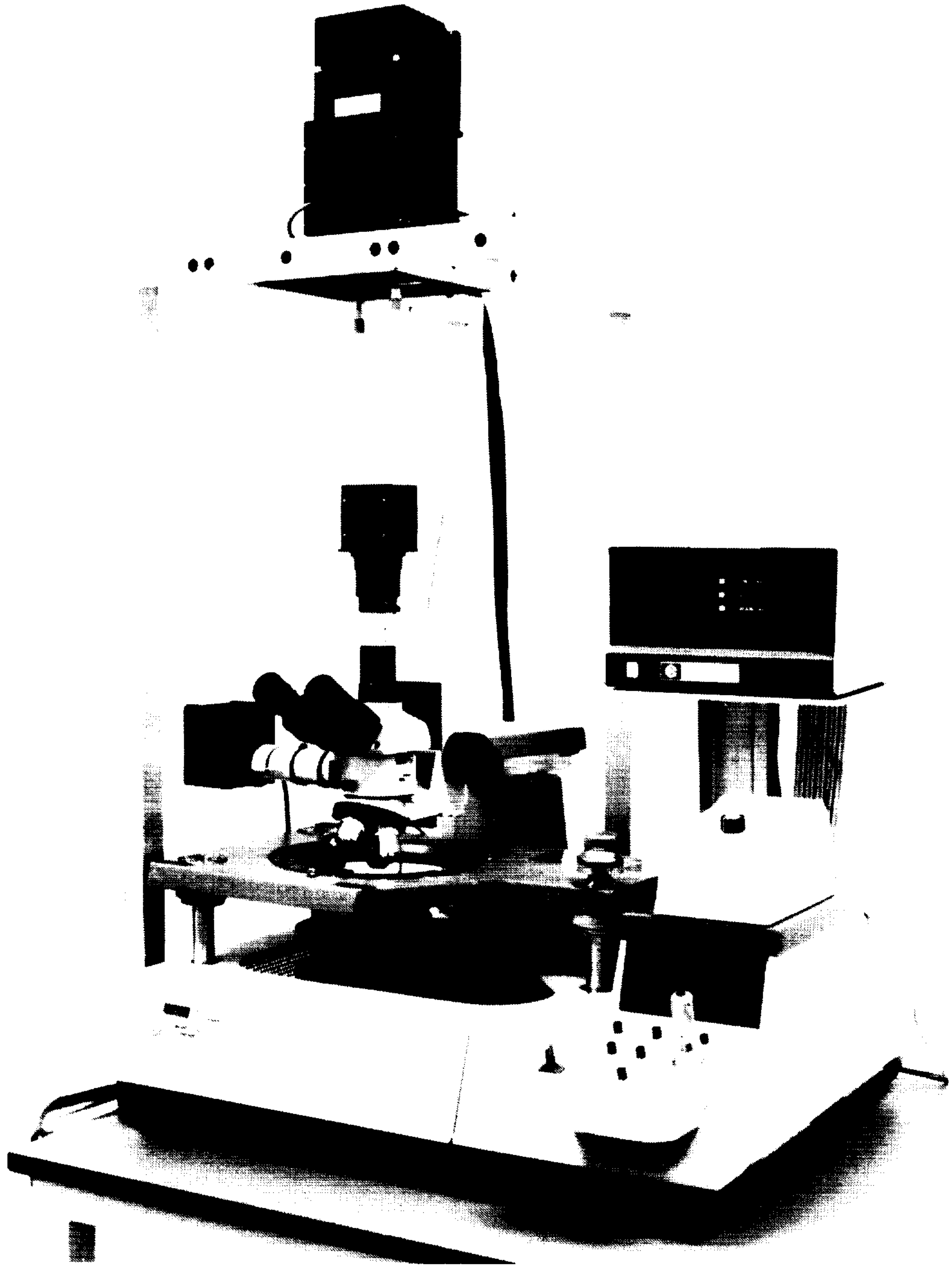

Figure 6. Concentrated Light Solar Cell Test Station

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Table 1. GaSb Cell Performance Progress

	Jun-1988	Mar-1989	May-1989	Sept-1989	Oct-1989
Isc (mA)	37	50	101	210	317
Voc (volts)	0.442	0.446	0.462	0.482	0.491
FF	0.66	0.7	0.72	0.69	0.745
Vmax (volts)	0.33	0.353	0.37	0.37	0.401
Imax (mA)	33	44	92	189	289
1 sun Isc (mA)	1.35	1.37	1.37	1.64	1.64
Concentration ratio	27.4	37	73	128	193
Filtered efficiency (%)	5.7	6.18	6.7	7.9	8.7
Covered efficiency (%)			8.2	9.1	9.6
Stacked efficiency (%)			7		

Table 2. Stacked GaAs/GaSb Test Article Performance Verification

Air Mass Zero Simulation

	Isc (mA)	Voc (volts)	FF	Vmax (volts)	Conx	Eff (%)
Boeing						
GaAs	70	1.100	0.84	0.984	38.2	23.7
GaSb	106	0.462	0.72	0.370	85	7.0
					Efficiency total	30.7
NASA						
GaAs	183	1.120	0.84	0.987	100	23.9
GaSb	125	0.469	0.71	0.367	100	6.9
					Efficiency total	30.8