30% EFFICIENT InGaP/GaAs/GaSb CELL-INTERCONNECTED-CIRCUITS FOR LINE-FOCUS CONCENTRATOR ARRAYS

Lewis Fraas[1], James Avery[1], Peter Iles[2], Charlie Chu[2], and Mike Piszczor[3]
JX Crystals Inc[1], Issaquah, WA 98027
Tecstar[2], Industry, CA 91745
NASA Glenn[3], Cleveland, OH 44135

Introduction

In 1989, Fraas and Avery demonstrated a world-record 31% efficient AM0 GaAs/GaSb tandem solar cell (1-5). This record efficiency still holds today. However, the GaAs/GaSb mechanical-stacked cell was designed to work with concentrated sunlight and at that time, the space community had no experience with concentrated sunlight solar arrays. So the photovoltaic community continued to work on improving flat plate cell efficiencies for satellite power systems. This work led to the adoption of the InGaP/GaAs/Ge monolithic tandem cell with an efficiency of 23%. Meanwhile in 1992, Fraas and Avery fabricated GaAs/GaSb cells and Entech supplied lenses for a concentrator min-module that was flown on the Photovoltaic Advanced Space Power (PASP) satellite. This mini-module performed well with high power density, excellent radiation resistance, and absolutely no problems with sun tracking. The success of the PASP module then led to the successful use of a 2.5 kW line-focus concentrator array as the main power source on Deep Space 1. Deep Space 1 was launched in 1998.

So now ten years later, concentrating solar photovoltaic arrays are proven. It is now time to bring a 30% efficient concentrator cell into production. We plan to do this by combining the InGaP/GaAs cell with the GaSb cell in a two-terminal triple-junction mechanical-stacked configuration. Herein, we describe a 30% efficient, lightweight, affordable cell-interconnected-circuit for line-focus concentrator systems. These two-terminal triple-junction mechanical-stacked cell-interconnected-circuits (TJ-MS-CICs) can be fitted into the concentrator panels of the type used on the Deep Space 1 (DS1) mission.

Over the past ten years, monolithic tandem cells have been used exclusively because they are preferred over stacked cells for flat plate arrays. However, it is noteworthy that stacked cells still out-perform the monolithic cells by a substantial margin. The reason why both the GaAs/GaSb stacked cell and the InGaP/GaAs/GaSb stacked cell out-perform the InGaP/GaAs/Ge monolithic dual junction (DJ) cell is really quite straight-forward. The monolithic DJ cell only uses the energy in the sun's spectrum between 0.4 and 0.9 microns while the GaAs/GaSb DJ cell and the InGaP/GaAs/GaSb TJ cell both use the much larger spectral range between 0.4 and 1.8 microns. Recently, there has been an attempt to close this performance gap by making the Ge junction active (6). However, the 26% efficiency recently demonstrated for the InGaP/GaAs/Ge monolithic triple-junction (TJ) cell still falls short of the 30% mark. There is a good reason for this as well. The problem with the monolithic TJ cell is that the Ge cell is automatically series connected with the DJ cell. However while the DJ cell only produces a 1 sun current of 16 mA/cm^2, both the GaSb and Ge cells are capable of producing 33 mA/cm^2. In the series connected configuration, the current in excess of 16 mA/cm^2 cannot be used. However, this is not a problem in the voltage-matched configuration used in mechanical-stacked circuits.

Even more recently, attempts have been made to close the performance gap by adding a fourth junction in the monolithic configuration. This has led to the InGaP/GaAs/GaInAsN/Ge cell. However to date, the quantum yields in the new GaInAsN cell have been poor (7).

This paper is divided into two sections. In the first section, we present data showing that 30% is real for the InGaP/GaAs/GaSb stacked cell. Then in the second section, we describe a simple two terminal circuit (TJ-MS-CIC) that mounts into line-focus arrays of the type used on Deep Space 1. In our view, a TJ-MS-CIC is actually much easier to produce than a InGaP/GaAs/GaInAsN/Ge cell.

Stacked Cell Performance

The original GaAs/GaSb mechanically stacked tandem cell was developed for point-focus systems. At 100 suns concentration, the GaAs cell converted 24% of the sun's energy to electric power while the GaSb cell boosted this efficiency by seven percentage points. However, the subsequently developed concentrator systems used line-focus optics operating in the 5 to 15 sun concentration range. The cells in DS1 operate at 7.5 suns. Since conversion efficiencies fall off at lower concentration ratios, we decided to build four terminal InGaP/GaAs/GaSb stacks and measure the performance of these stacks in the 5 to 15 suns range. We anticipated that the InGaP/GaAs DJ cell efficiency would be at least 25% with the GaSb cell providing a five percentage point boost. In a Phase I BMDO SBIR contract effort, Tecstar provided InGaP/GaAs cells to JX Crystals and JX Crystals fabricated the GaSb booster cells and the stacks. An efficiency of 29.6% was demonstrated during this phase I activity.

While our efficiency goal was achieved, there still were some surprises. The good news was that the GaSb cell boost efficiency of 6.3% at 15 suns was higher than anticipated as can be seen in table I. Furthermore, the GaSb cell performances were very tightly grouped.

However, this good news was compensated by a lower than expected performance from the InGaP/GaAs DJ cells. While the DJ cell efficiencies were tightly grouped around 22.7% at 1 sun (table II), the performances at 15 suns varied significantly as can be seen in table III.

While the best DJ cell had an efficiency of 23.3% at 15 suns, the efficiency for the worst cell was only 14.9% and the best cell efficiency was well below the 25% efficiency anticipated. Still from a global perspective, the lower than expected performance for the InGaP/GaAs cell was compensated for by the higher than anticipated performance from the GaSb cell such that the overall performance anticipated was achieved.

The scatter in the performances associated with the DJ cell can be attributed to the tunnel junction between the InGaP and the GaAs cells as can be seen in the current vs. voltage curves shown in figure 1. However, the cells we received predated DS1. We have been assured that this problem has now been solved.

Using the cells available to us in the Phase I effort, three stack assemblies were fabricated as shown in the photograph in figure 2. The performances for these three stacks are summarized in table IV.

Practical Two-Terminal Circuits

In our phase I effort, we demonstrated that 30% efficiency can be achieved at the cell level. Stated differently, given the highest performance DJ cells available commercially, we demonstrated that the GaSb cell can boost performance by 6.3 percentage points. This means that the Deep Space 1 array type output of 2.5 kW can be increased to 2.5kW x (23.3+6.3) / 23.3 = 3.2 kW. This is a very substantial improvement. However in order to realize this gain, we first need to describe how these cells can be successfully integrated into circuits and modules.

The InGaP/GaAs/GaSb articles tested in phase I were four terminal devices. The solar power community is accustomed to two terminal structures. Figure 3 shows a drawing of a simple two-terminal triple-junction mechanical-stacked cell-interconnected-circuit (TJ-MS-CIC) that can be used as an array building block. The TJ-MS-CIC shown is simply a 1.8 cm by 6.1 cm two-terminal 30% efficient circuit. It consists of an alumina substrate with seven GaSb cells wired in series and two InGaP/GaAs cells wired in parallel. It also contains a bypass diode to protect the DJ cells. The series and parallel cell interconnect scheme used is called a "voltage matching" configuration. It is based on the fact that seven times the maximum power voltage for a GaSb cell (7x0.34 V=2.38 V) is equal to or slightly larger than the maximum power voltage of the InGaP/GaAs cell (2.27 V).

The InGaP/GaAs cells are similar in size (1.2 cm by 3.0 cm) to the cells used in the receiver circuits on DS1. However, the InGaP/GaAs cells used here are made transparent in the infrared by growing the active layers on a thin GaAs substrate.

TJ-MS-CICs are made simply as follows. First thin GaSb cells (0.85 cm x 1.2 cm) are solder bonded to the alumina substrate. This is done rapidly with an automated pick-and-place machine. Then these cells are connected to the circuit traces shown at the right of the circuit in figure 3. This is done with an automated ribbon bonder. The DJ cells are supplied with leads already attached. These cells are then adhesive-bonded on top of the GaSb cells with silicone adhesive and the leads are then welded to the circuit traces shown to the left on the circuit in figure 3. The DJ cell lead welding is done with the same automated ribbon bonder that was used previously for the GaSb cell ribbon bonding. While the TJ-MS-CICs shown here in figure 3 is novel, this assembly procedure is similar to that used in fabricating the first concentrator PASP module flown in space in 1994. So the materials and procedures are already proven.

So far in this discussion, we have focused on a primary goal: to provide for increased energy conversion efficiency. This goal translates to a higher power per unit area for the array. However, there are additional goals. We want light weight for more Watts per kg. We also want to know that the TJ-MS-CICs can be produced in quantity at a reasonable cost. In the following, we address each of these additional goals.

The TJ-MS-CIC is attractive because it is lightweight. Table V summarizes the weight contributions to these CICs. Two alternate cell thicknesses are presented based on 4 mil or 8 mil thick component cells. In the lighter DJ configuration, the 8 mil thick GaAs substrate used during epitaxy will be thinned to 4 mils at some point during subsequent processing prior to being bonded to a glass superstrate. Similarly, 4 and 8 mil thick GaSb cells are possible with the base line being the 8 mil thick cell. The TJ-MS-CIC weight in the light configuration corresponds to 0.34 kg/m^2 (aperature). The alternate heavier but more conservative configuration assumes 8 mil thick substrates. In this configuration the TJ-MS-CIC weight is 0.51 kg/m^2. In either case our TJ-MS-CICs are lighter than the receiver used in DS1.

The impact of these circuit weights at the array level can be inferred from the following comparisons. If the 30% TJ-MS-CICs were to have been used on DS1, the panel power density would have increased from 200 W/m^2 to 260 W/m^2. With the lighter CICs (heavier CICs), the power to weight density would have increased from 47 W/kg to 64 W/kg (62 W/kg). Given a 260 W/m^2 panel, the panel weight would have to decrease to 2.6 kg/m^2 in order to achieve 100 W/kg. If 100 W/kg were required, the CIC weights would still be small compared to this required panel weight.

In order to address the cost issue, note that the industry array cost target is $200 per Watt. Also note that a TJ-MS-CIC will generate approximately 1.25 W of which the GaSb cell contributes about 0.25 W. If a 1 W DJ cell plus lens and support structure cost $200, then a TJ-MS-CIC plus lens and support structure would be competitive at a cost of $250. This means that all else being equal, the 7 GaSb cells and circuit assembly cost allowance is $50 per TJ-MS-CIC. This gives us a target of $5 per GaSb cell and $15 for assembly per CIC.

We begin by noting that the additional cell, the GaSb cell, is easy and inexpensive to fabricate. Its fabrication process is similar to the silicon cell manufacturing process. We use converted silicon crystal pullers for the GaSb crystal growth and diffusions for junction formation. In contract to the InGaP/GaAs/Ge cell, no epitaxy is required and no toxic gases are required. The materials cost of the Ga and Sb in a GaSb cell add up to only 14 cents / cm^2. So in high volume production, the GaSb cell should be inexpensive compared to the InGaP/GaAs/Ge cell. JX Crystals already makes thousands of GaSb cells per year for TPV applications.

Besides the additional cost of the GaSb cell, there will also be the costs associated with circuit assembly. As previously pointed out the circuit assembly tasks can be automated. The TJ-MS-CIC die bonding step can be done with an automated pick-and-place machine. JX Crystals already has such a pick-and-place machine operating at its facility for the fabrication of TPV circuits. A photograph of this machine is shown in figure 4.

The remaining circuit assembly task is lead bonding. This task can also be automated using the ribbon bonder shown in figure 5. The microscope shown in the photo of this machine is for initial alignment only. After initial setup and part loading, both the pick-and-place and the ribbon bonder have vision recognition systems enabling automated operation.

Summary

In summary, the time is now right to bring the 30% mechanical-stacked concentrator cell described here into the main stream. The component technologies for this approach are already in place and in any case, there is no other near term approach that can rival the performance of this approach. The fact that 30% stacks have once again been demonstrated combined with the recent success of Deep Space 1 implies that this approach represents a minimal risk path to dramatically improved performance.

References

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Table I: JXC GaSb Booster Cell Performance Near 15 Suns AM0.

	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
	0.722	0.426	0.477	0.419	0.350	0.147	6.32
	0.711	0.428	0.478	0.415	0.351	0.146	6.28
	0.712	0.428	0.485	0.433	0.341	0.148	6.36
	0.716	0.429	0.476	0.425	0.344	0.146	6.28
	0.714	0.430	0.474	0.417	0.350	0.146	6.28
	0.713	0.430	0.484	0.427	0.348	0.149	6.41
	0.719	0.430	0.472	0.422	0.346	0.146	6.28
	0.724	0.431	0.471	0.425	0.346	0.147	6.32
average	0.716	0.429	0.477	0.423	0.347	0.147	6.32
%stdev	0.67	0.37	1.08	1.39	0.99	0.77	0.77

Table II: Tecstar Cell IV Data at 1 Sun AM0

Cell#	Voc (volts)	Isc (amps)	FF	Eff (%)
34	2.36	17.2	0.85	23.1
37	2.36	17.4	0.82	22.7
38	2.36	17.1	0.85	22.9
41	2.36	17.5	0.82	22.7
42	2.36	17.5	0.81	22.4
43	2.37	17.3	0.83	22.7
47	2.37	17.3	0.84	22.9
48	2.36	17.5	0.82	22.7
62	2.35	17.7	0.82	22.9
67	2.35	17.6	0.82	22.7

Table III: Tecstar Cell IV Data Flash Tested Near 15 Suns AM)

Cell#	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
34	0.781	2.53	0.267	0.240	2.20	0.528	22.7
37	0.684	2.53	0.264	0.216	2.11	0.457	19.6
38	0.559	2.52	0.247	0.178	1.96	0.348	14.9
41	0.754	2.52	0.271	0.244	2.11	0.514	22.1
42	0.618	2.51	0.266	0.217	1.90	0.411	17.6
43	0.761	2.55	0.265	0.233	2.20	0.513	22.0
47	0.798	2.53	0.269	0.238	2.29	0.543	23.3
48	0.716	2.53	0.233	0.191	2.22	0.423	18.2
62	0.713	2.52	0.272	0.228	2.15	0.490	21.0
67	0.710	2.54	0.276	0.228	2.18	0.496	21.3

Table IV: Stacked Cell Flash Test Data at 15 Suns AM0

Type	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
GaInP/GaAs	0.749	2.50	0.257	0.232	2.08	0.481	21.2
GaSb	0.706	0.429	0.497	0.444	0.339	0.150	6.56
			Combined Efficiency of Stack # 3				**27.8**
GaInP/GaAs	0.803	2.54	0.264	0.237	2.27	0.538	23.3
GaSb	0.687	0.427	0.501	0.437	0.336	0.147	6.26
			Combined Efficiency of Stack # 4				**29.6**
GaInP/GaAs	0.774	2.54	0.259	0.232	2.20	0.510	22.3
GaSb	0.715	0.431	0.500	0.445	0.347	0.154	6.62
			Combined Efficiency of Stack # 5				**28.9**

Table V: Receiver weight parameters

Part	Density G/cc	Area cm^2	Thickness cm	Mass/Lens kg/m^2
Cover	2.6	1.2x21	0.01	0.039
Adhesive	1.0	1.2x21	0.005	0.007
Top Cell	5.4	1.2x21	0.01	0.080
Adhesive	1.0	1.2x21	0.005	0.007
Bottom Cell	5.6	1.2x20	0.01	0.084
Solder	8.8	1.2x20	0.005	0.006
Base	4.0	1.8x21	0.012	0.108
Adhesive	1.0	1.8x21	0.005	0.010
		Total (light)		**0.341**
Top Cell	5.4	1.2x21	0.02	0.162
Bottom Cell (alternate)	5.6	1.2x21	0.02	0.168
		Total (heavier)		**0.515**

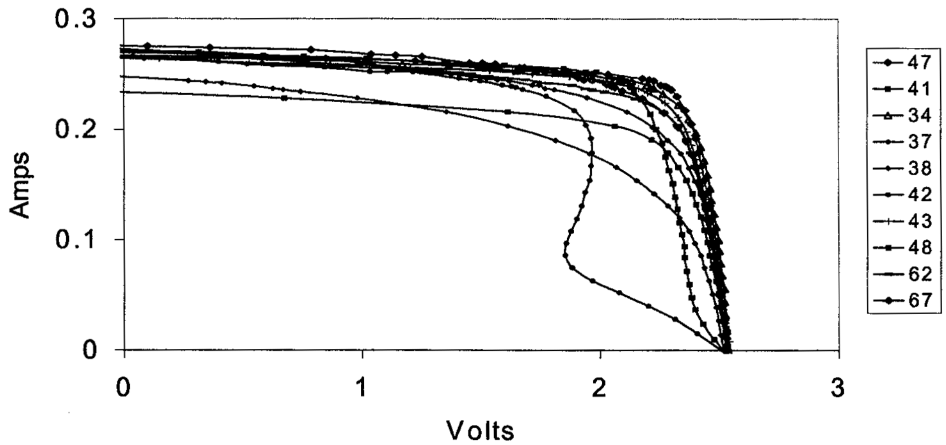

Figure 1. Dual Junction IV Curves Near 15 Suns AM0

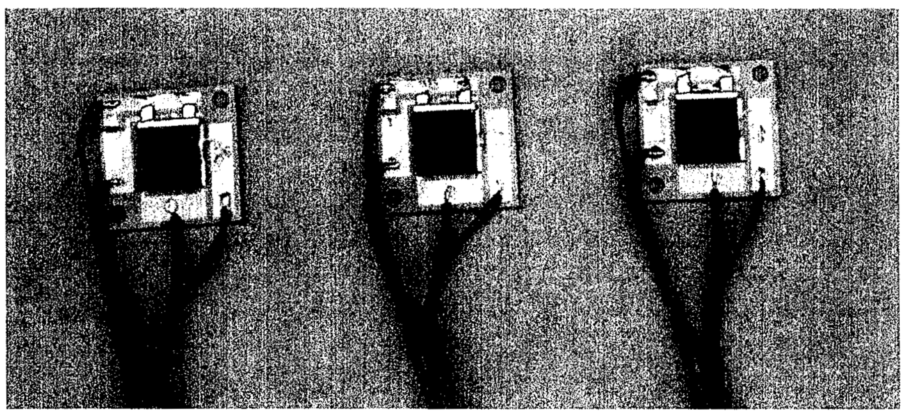

Figure 2. Dual Junction $GaInP_2/GaAs$ on GaSb Mechanically Stacked Test Articles

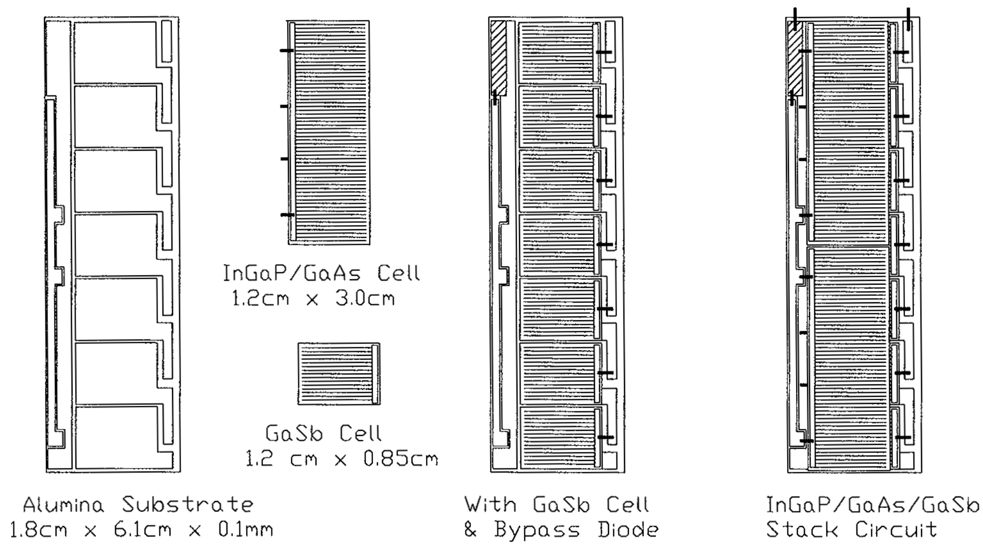

Figure 3: Triple-Junction Mechanical-Stacked Cell-Interconnected-Circuit (TJ-MS-CIC)

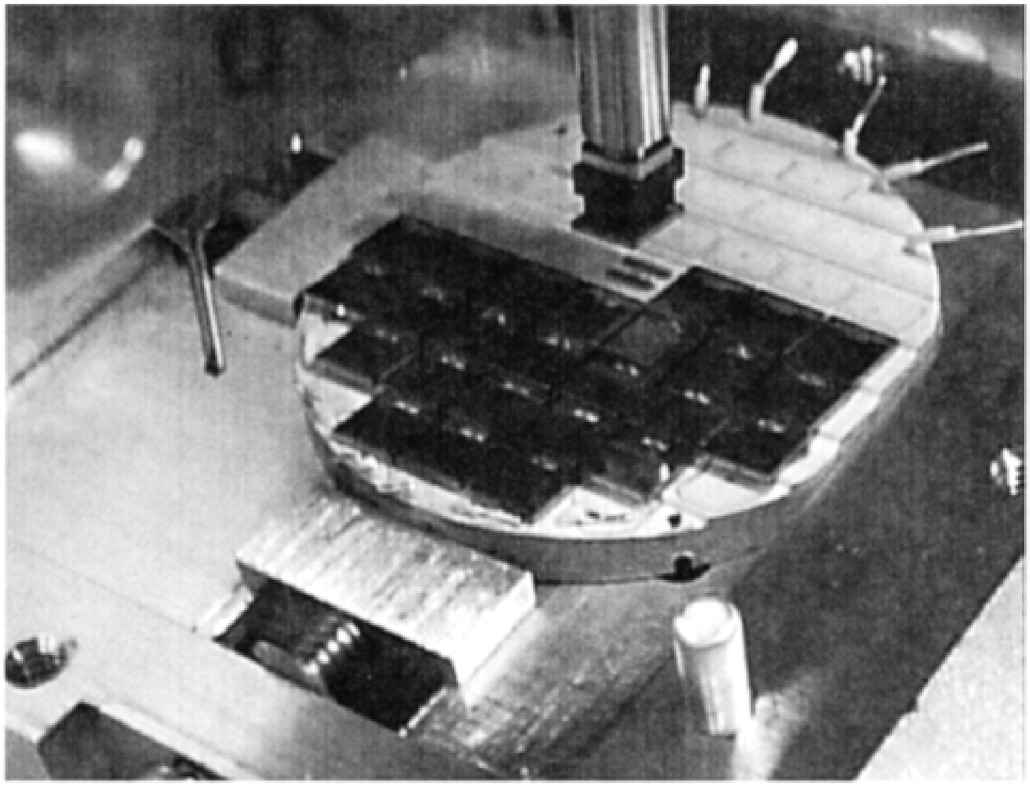

Figure 4: Automated Pick and Place machine for circuit assembly at JX Crystals

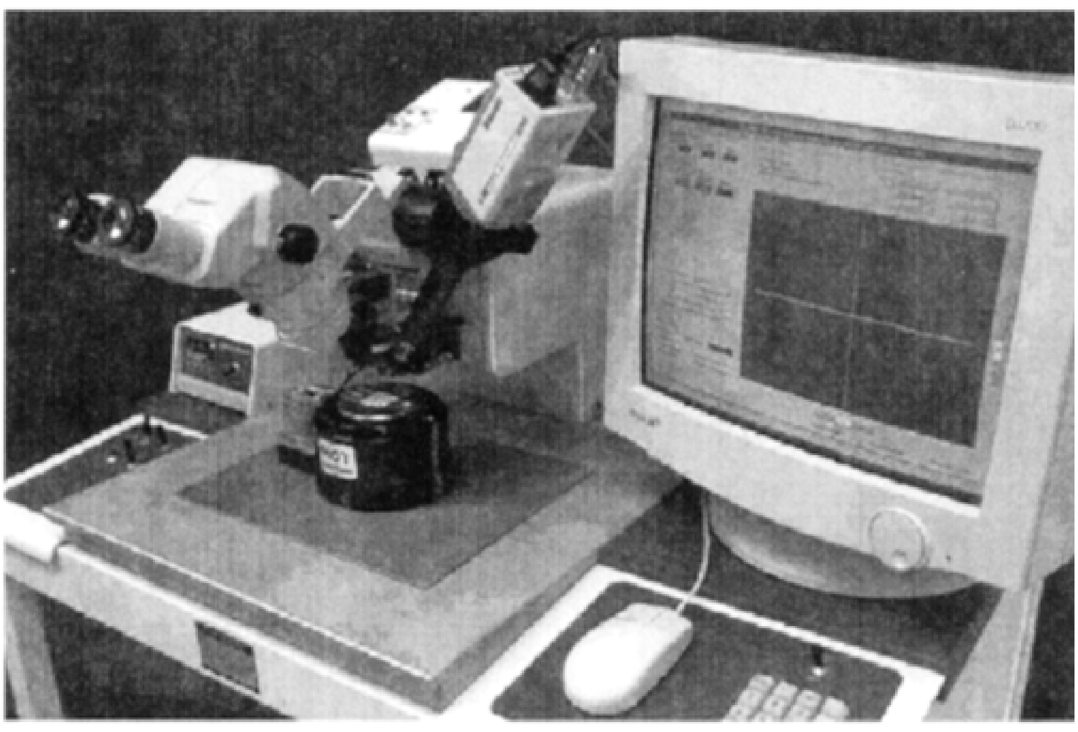

Figure 5: Automated wire bonder to be purchased by JX Crystals