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InGaP Photovoltaic Array Packaging Comparison

by Jeff Read Jr, Marc Litz, Muhammad Khan, Randy Tompkins, Arthur Harrison, Stephen Kelley, and David Baker

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14. ABSTRACT
Renewable energy sources such as photovoltaic (PV), alphavoltaic (AV), and betavoltaic (BV) devices are semiconductor energy conversion devices that can provide energy for long periods of time and—in the case of AVs/BVs—can operate in extreme conditions. These compact power sources are uniquely qualified to support unattended remote sensors, early warning electronics, and unmanned systems that increase situational awareness and Soldier effectiveness with small quantities of distributed energy for mobility and duration. In this technical report, we describe the fabrication and packaging process development of InGaP PV devices for both single-cell and four-cell InGaP devices in a series-wired quad array to match the voltage of conventional Li-ion batteries for the purpose of recharge. Current-voltage (IV) measurements of single InGaP cells produced approximately 60 µW output power under indoor lighting and 13 mW when exposed to direct sunlight. The power output at 45° incident was reduced to 75% of the original. A quad array of InGaP devices produced 57 mW under 1-sun intensity. These devices and the packaging of arrays are used as a proxy for BV components and system designs that would share the same process steps for BV-array fabrication.

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1. Introduction

This report describes the use of InGaP photovoltaic (PV) cells to create a 4 cm^2 compact power source. The PV array assembly is a proxy for betavoltaic (BV) power sources that are in waiting-mode for array fabrication. The PV array is also a useful compact power source for small electronics. An example of an unattended sensor that is a ready recipient of this power source is the ANT (Autonomous 'N Tiny) EH (electric and magnetic) sensor demanding 200 µW average power, which is being developed by the US Army Combat Capabilities Development Command Army Research Laboratory for transmission-line load sensing (as shown in Fig. 1). The described PV arrays can be assembled in the laboratory without special handling procedures required for radioisotope BV versions to come. Section 2 describes the options for packaging and the challenges each presented when using the InGaP devices. Section 3 describes the measurement of electrical output under indoor and outdoor conditions.

Fig. 1 EH sensor (3 × 5 × 2 inches with PV power source)[*]

1.1 Solar Radiation

The temperature at the surface of the sun is approximately 6000 K. The solar spectrum fits the blackbody radiation curve shown in Fig. 2. The total power received by the sun on earth is 1360 W/m^2 or often approximated by the 1 kW/m^2 received on the surface of the earth. The power emitted by the sun can then be calculated by taking the effective surface of a sphere at the radius of 93M miles, 4 Πr^2, and then multiplying by 1360 W/m^2, to get a result of 5.77×10^{25} W emitted by the sun. The energy consumed in the United States is approximately 100 quads (1.05×10^{20} J), which averages to 3.3 TW power consumption.[1]

[*] Used with permission from Kathleen Coleman (DEVCOM ARL, FCDD-RLS-EM).

To generate 3.3 TW at noon we would need an array of 7340 km^2 (less than the size of Juneau, Alaska) in the desert area of Arizona or New Mexico.

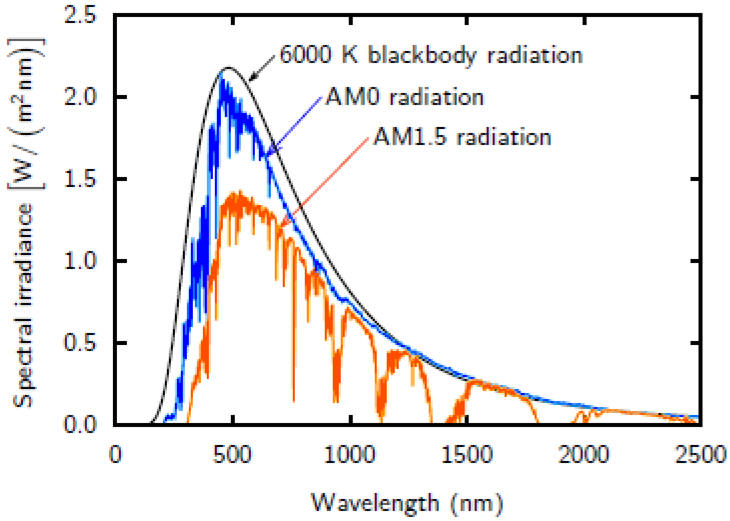


Fig. 2 Solar spectra: The blackbody spectrum of a blackbody at 6000 K, the extraterrestrial AM0 spectrum, and the terrestrial AM1.5 spectrum

1.2 Photovoltaic Materials

A variety of PV materials have been developed for use in converting photon energy from sunlight into electrical power. Silicon cells are the most common of all PV materials. Silicon is the second most abundant material in the earth's crust[2] and the simplest and most mature of all semiconductors. Table 1 lists common PV materials with information on electronic bandgaps, and so forth. The properties of ternary compounds (InGaP and AlGaN) can vary depending on the composition. The bandgap shown in Table 1 for the ternary compounds are for the simplified composition ratios ($In_{0.5}Ga_{0.5}P$ and $Al_{0.1}Ga_{0.9}N$). The direct bandgap semiconductors are used for LEDs because the crystal momentum of electrons and holes is the same for both the conduction band and the valence band; therefore, an electron can directly/efficiently absorb or emit a photon. However, energy conversion from electrons (betas) in BVs benefits more from indirect bandgap materials because the longer diffusion length enables a larger charge collection from volume outside the depletion region. Higher mass density materials also benefit BV application because the electron energy is absorbed in a shorter range that better matches the electron penetration depth with depletion region thickness.

Table 1 **PV material response curves are dominated by their bandgap and corresponding wavelength. Photons with energy less than that of the bandgap (larger wavelength) are transmitted through the material and cannot be converted to electrical power.**

Material	Bandgap (eV)	Wavelength (nm)	Type	Density (g/cc)
Ge	0.67	1854	Indirect	5.50
Si	1.10	1129	Indirect	2.33
GaAs	1.43	869	Direct	5.32
InGaP	1.84	675	Indirect	4.81
GaP	2.25	552	Indirect	2.26
ZnS	2.35	529	Direct	4.09
GaN	3.50	355	Direct	6.10
ZnS	3.90	319	Direct	4.09
AlGaN	6.10	204	Direct	6.51

1.3 InGaP Triple Junction Space Solutions

Space-grade solar cells are the primary power source for orbiting platforms, and therefore serve as an excellent example for comparison to the results of this PV array task. They are made up of three semiconductor materials that cover the solar spectrum with more efficiency than any one homojunction. InGaP, InGaAs, and Ge have been successfully combined and manufactured for the demanding reliability of space-based power generation. The use of PV is limited to distances within the radius of the sun to Saturn because outside of this orbit the solar output is too low to be useful. InGaP, which matches the blue/green visible region, is the most efficient material for the most demanding of all solar cell applications (space). Our use of InGaP semiconductor cells is predicated on the fact that it is the best match to energy converting phosphors used in BV applications. The external quantum efficiency of InGaP is shown in Fig. 3.

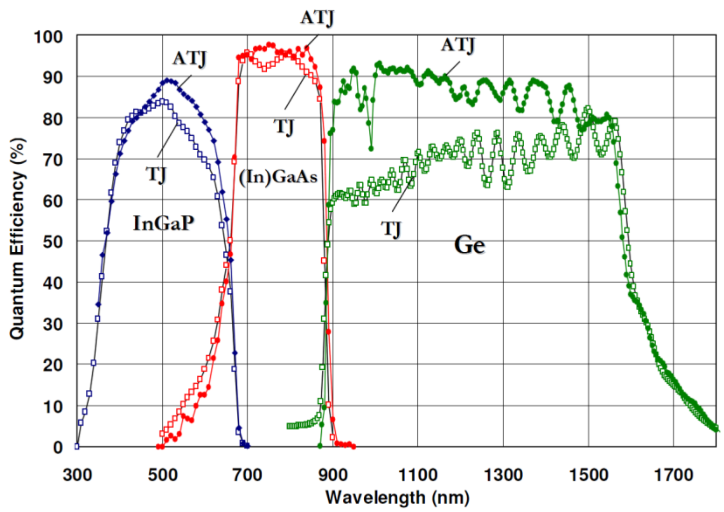


Fig. 3 The external quantum efficiency (EQE) of InGaP, InGaAs, and Ge, which constitute a three junction III-V solar cell, is shown.[3,4] EQE is the ratio of charge collected to incident photons.

1.4 BV Radiation

A BV device is an energy converter that transforms the kinetic energy from particles as a result of radioactive decay into electrical energy. Radioactive particles are emitted from radioisotopes (H-3, Ni-63, Pm-147, etc.) and are absorbed into a semiconductor. The radioisotopes we are considering have high-energy density but low-power density—the opposite of chemical storage batteries. The half-life of these radioisotopes is measured in years, which means they emit energy for long periods of time, making them an ideal energy source for extended duration operating requirements. Radioisotopes can decay in the form of alphas, betas, gammas, positrons, or electron capture.[5] Of these decays, low-energy beta particles are the safest for human interaction/use. Initially, higher energy radioactive particles were tested but were determined to be too damaging to the semiconductor materials for long-term use; therefore, H-3, Ni-63, and Pm-147 became the standard as harmless beta emitters (Table 2).[6] While foil radioisotopes can simply be laid on the surface, we have developed methods of reservoir creation to contain the liquid radioisotopes atop the energy converter.[7,8]

Table 2 β-emitter radioactive decay properties[9]

β-emitter	Half-life	Average energy (keV)	Maximum energy (keV)	Average spec. power (mW/g)
H-3[a]	12.32 years	5.69	18.59	324.914
Ru-106[a]	1.02 years	10.03	39.40	196.948
Ni-63[a]	100.2 years	17.42	66.94	5.796
S-35[a]	87.37 days	48.76	167.33	12,339.148
Pm-147	2.62 years	61.93	224.60	340.367

BVs and PVs work through the transfer of kinetic energy.[6] When betas collide with semiconductor material, the transferred energy is used to raise electrons through the valence bands around an atom until they are free or there is no energy left to transfer. The electron's absence leaves a hole, and together we refer to them as an electron-hole pair (EHP). Unlike photons, which usually generate one EHP, betas can produce many EHPs.[10] The EHPs generated within or near the depletion region then separate due to the built-in electric field and flow to the side of their respective charge. The built-in electric field can be in the form of a p–n junction or a Schottky diode. Current will not flow without a diode present, since the EHPs will recombine in the semiconductor material without an electric field to separate them.

1.5 Arraying PV/BV Devices

The goal of using the long-lived lower-power BV to trickle charge short-lived higher-power chemical storage batteries suggests connecting the 1-V BV cells in series to reach the 4-V nominal operation of the Li-Ion chemical battery. The combination of series and parallel connections may lead to several problems in PV arrays when cells have different performance characteristics. This condition results in detrimental effects of power loss. These challenges are often mitigated using bypass diodes and reduced cell shunt resistance.[11] When cells are connected in series, the current-voltage (I-V) data shows that the current output of the shaded cell significantly limits the current and hence power output of the array. In extreme cases, almost the entire array output can be lost through shading of a single cell. Furthermore, when the array reaches short circuit condition, the low current output cell is severely reverse-biased, while the other cells operate at near their maximum power point (MPP). When the power output of the array is zero, all the power generated by the unshaded cells is dissipated in a single adjacent shaded cell, resulting in localized heating of the cell from which degradation and possible cell damage can occur.

2. Packaging

2.1 Evaluation of Manufactured InGaP Chips

The commercially available InGaP cells used in this research were fabricated by MicroLink on 6-inch wafers and subsequently diced into 1-cm^2 pieces. Each wafer contains 112 InGaP chips arranged in a grid pattern as shown in Fig. 4. To assess yield across the wafer, the individual 1-cm^2 cells were measured with an IV curve tracer to determine whether they are suitable for inclusion into the proposed PV array; the device performance can vary across a 6-inch wafer due to the manufacturing processes. A Keithley 2450 source meter in conjunction with a Raspberry Pi and Python software (shown in Fig. 5) were used to apply a voltage, from –5 V to +5 V to each device and then the corresponding current was recorded. Once the data was collected, the IV curves were plotted and analyzed using our team's Matlab source code. Under room light, these InGaP cells produce a short circuit current (Isc) in the tens of μW and an open-circuit voltage (Voc) around 1.1 V. In the dark, InGaP cells produce an Isc in the tens of nA and a Voc around 0.8 V. These measurements are used to filter devices for quality control where ultimately low-leakage diodes were chosen for use in our packaging research and quad-array fabrication.

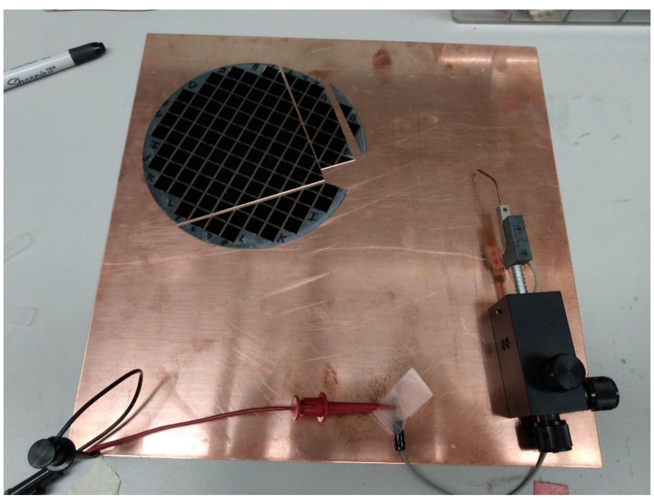


Fig. 4 Testing probe and back copper contact shown, as well as an InGaP wafer that has broken into several pieces

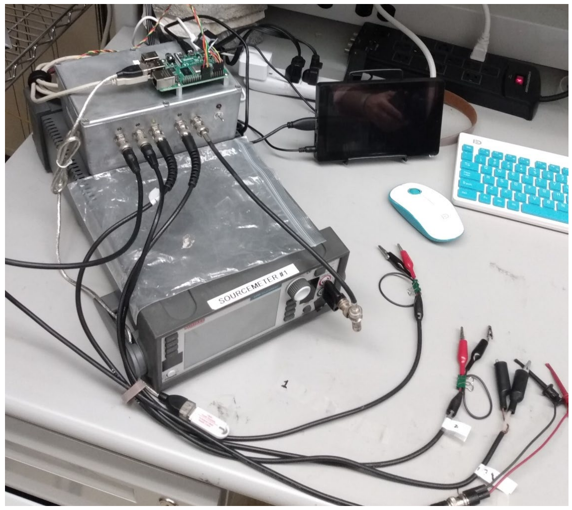


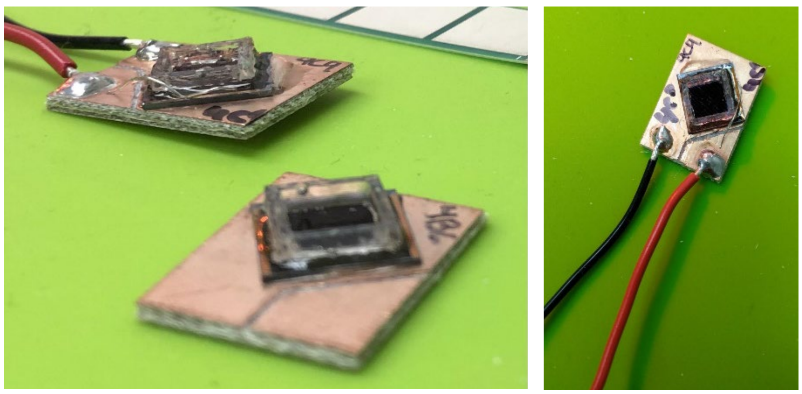
Fig. 5 The Raspberry Pi, Keithley 2450 sourcemeter, and splitter box are shown; all are attached to a compact 7-inch display

2.2 Reservoir Creation for BV Application

To contain the Ni-63 or Tritium radioisotopes, we needed to design, fabricate, and secure a UV-cured epoxy reservoir to the InGaP chip. A UV-cured adhesive (BONDIC brand) is an ideal reservoir material because it is waterproof, durable, and can be quickly formed and cured. A silicon mold was made from a sheet of cured silicone using a razor blade. The Si mold was then filled with UV-cured resin and peeled from the silicone mold because silicone is a very good non-adhesive polymer. However, using a razor blade to carve the molds was not ideal; after removal from the silicone mold, the reservoirs were misshapen and a rough bottom surface lead to a poor seal against the flat InGaP devices. We needed to create a mold that could be filled with silicone monomer, and once the silicone polymer was cured, would produce a clean, smooth mold with consistent shape mimicking that of the silicone mold. With this in mind we pivoted to using 3-D printed plastic molds. We used Solidworks 2019 software to design the mold and a Makerbot Replicator 2X that used an ABS filament was used for printing. Once the reservoirs were created, they were mounted onto the cells and sealed with additional UV-cured resin. The resulting mounted reservoir was filled with isopropyl alcohol to verify the seal.

2.3 Mounting and Arraying

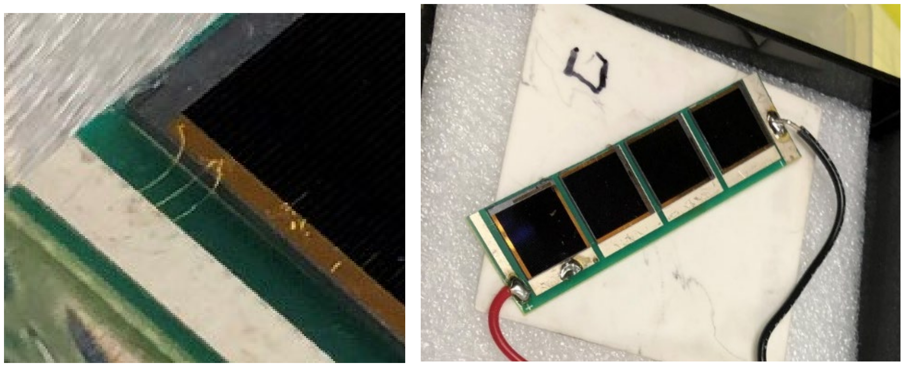
The mounting process begins with cutting a wafer board sheet of copper-FR4-metal into small coupons of about 1.0 × 1.5 inches. A slit is then carved into the corner of each coupon using a razor to separate the positive and negative connections, with the negative side taking up the majority of the space. The coupon is then labelled on both sides with the unique identity of the InGaP cell. A touch of silver epoxy is used to attach a chip/cell to the copper board on the negative side, close to the positive section, and UV-cured resin is used to seal the reservoir onto the InGaP chip (Fig. 6a). The positive side is then wedge-bonded to the top contact bar on the device (Fig. 6b). Positive and negative leads are soldered to the copper board. The final step includes bonding reservoirs to the center of the device. The UV-cured adhesive may also be applied to the wedge bonds to ensure they are protected. At this point, a PV device has been prepared and is ready to be fabricated into a BV device with the loading of radioisotope material. Instructions for the packaging process are described in greater detail in the Appendix.



a **b**

Fig. 6 a) Mounted InGaP chip with reservoir sealed on top; and b) Fully fabricated PV device with reservoir for isotope application

Arraying devices present the potential for shorting cells, introducing resistive losses in bonding techniques, and current limiting from the weakest cell. Wire bonding was found to be the least mechanically robust compared to wedge bonding or soldering. The wire bonds are shown in Fig. 7 for a linear array device. Initially, the 2 × 2 array recorded 4.1 Voc and 60 µA 246 µW MPP. However, it became damaged through mishandling (details are unclear), at which point it measured only 3 Voc and 49 µA, providing approximately 150 µW at the MPP stimulated from indoor lighting. This reduced voltage indicates that one of the InGaPs shorted between the bonding and the testing phase of the process—although no damage to the contact bar or device was visible and the measurements were taken with the same setup in the same lighting conditions. Wire bonds are the least mechanically robust of all the bonding approaches utilized in this fabrication effort. In the future, an adhesive will be applied to protect the location of the wire bond. The reduced current can be attributed to either resistance through the wire bonds, poor series resistance in one of the InGaP cells, or a shorted InGaP cell.



a b

Fig. 7 a) Gold wire bond: 0.7 mm; and b) linear array of four InGaP cells in series

Mounting the devices presented obstacles that required consideration. One complication came with the silver epoxy used to secure the InGaP chip to the board, which was a necessary adhesive, since it was conductive and provided a strong bond between the backside metal contact and board. The silver paint required heat to cure, and because InGaP devices decompose at high temperatures, samples sat under a heat lamp for 2–3 days for proper mounting. Future work could involve investigating a conductive adhesive that does not take significant time for mounting and curing. In addition to the conductive adhesive, a quick-setting, nonconductive UV-cured epoxy was applied around the edge of the InGaP cell to help mechanically hold the PV cell onto the wafer board. It was applied with a dental pick to the edges of the cell without it seeping underneath or onto the contact.

The most challenging part of the process is wire bonding. Often bonds end up breaking or shorting, which damages or degrades the entire array. An individual InGaP chip can also fail after being soldered and bonded to an array, and is difficult, if not impossible, to remove and replace. Therefore, alternative methods of cell connection and replacement were attempted using copper tape. This approach had issues because of poor adhesion with the copper tape's backside. The copper tape would not remain attached to the top contact even with the application of silver epoxy and was impossible to place accurately on the 100-µm PV contact. It was therefore determined that copper tape was not superior to wire bonding.

2.4 Wire Bonding

Two wire bonding techniques, ball bonding and wedge bonding, were employed during the mounting and arraying process. Each process has its advantages and disadvantages, and both require specialized equipment and a skilled operator. Gold ball bonding uses 0.7–2.0 mil wires to achieve small, precise bonds.[12] A gold ball is formed through a high-voltage shock to the tip of the wire. This ball is then pressed onto the die or contact and is heated through vibrations from an ultrasonic frequency, at which point it melts and bonds to the surface. The tip is then moved to the second contact point and a similar process occurs, except the bond is wedge-shaped and the wire is cut upon completion. An experienced craftsman can form a loop between the two points to elevate the wire and reduce shorting. Three ball bonds were made for each device to optimize resistance through the wire by accounting for any poor contact spots, and to provide safety bonds in case one breaks. Ball bonds are incredibly sensitive and gold wires are thin, so these arrays must be handled carefully.

2.5 Wedge Bonding

Wedge bonding, on the other hand, is much more durable because it uses thicker aluminum wire and a larger bond contact area; however, it lacks the precision of ball bonding. As with the ball bonder, the wedge bonder tip applies force and an ultrasonic frequency to melt the wire until it bonds with the device, but the bonds are formed in an oblong wedge shape, taking up more surface area and providing a stronger connection.[13] Initially, one wedge bond was used on each device in the array, and the voltage measured under illumination was 3.7 V. Upon the addition of a second bond to each device, the voltage improved to 4.1 V, a 0.4 V increase. This demonstrates the practicality of additional bonds and suggests that there is variation across the sample with wire-bond/metal contact interface resistance.

3. Measurement and Results

3.1 Performance of Single Cell Dark, Indoor, Outdoor

A single InGaP cell was stimulated by a Thermo Oriel 68902 solar simulator in Bldg. 207, 2B038. The measured electrical output was 1.2 Voc and 13.7 mA Isc with an MPP of 14.9 mW. The calculated fill factor (FF) was 87.2%. The active area of the InGaP cell is 9 × 9 mm^2, resulting in a current density of 18.4 A/cm^2 (Fig. 8a). The MPP at 45% incidence is 11.2 mW, or 75% of MPP at normal incidence.

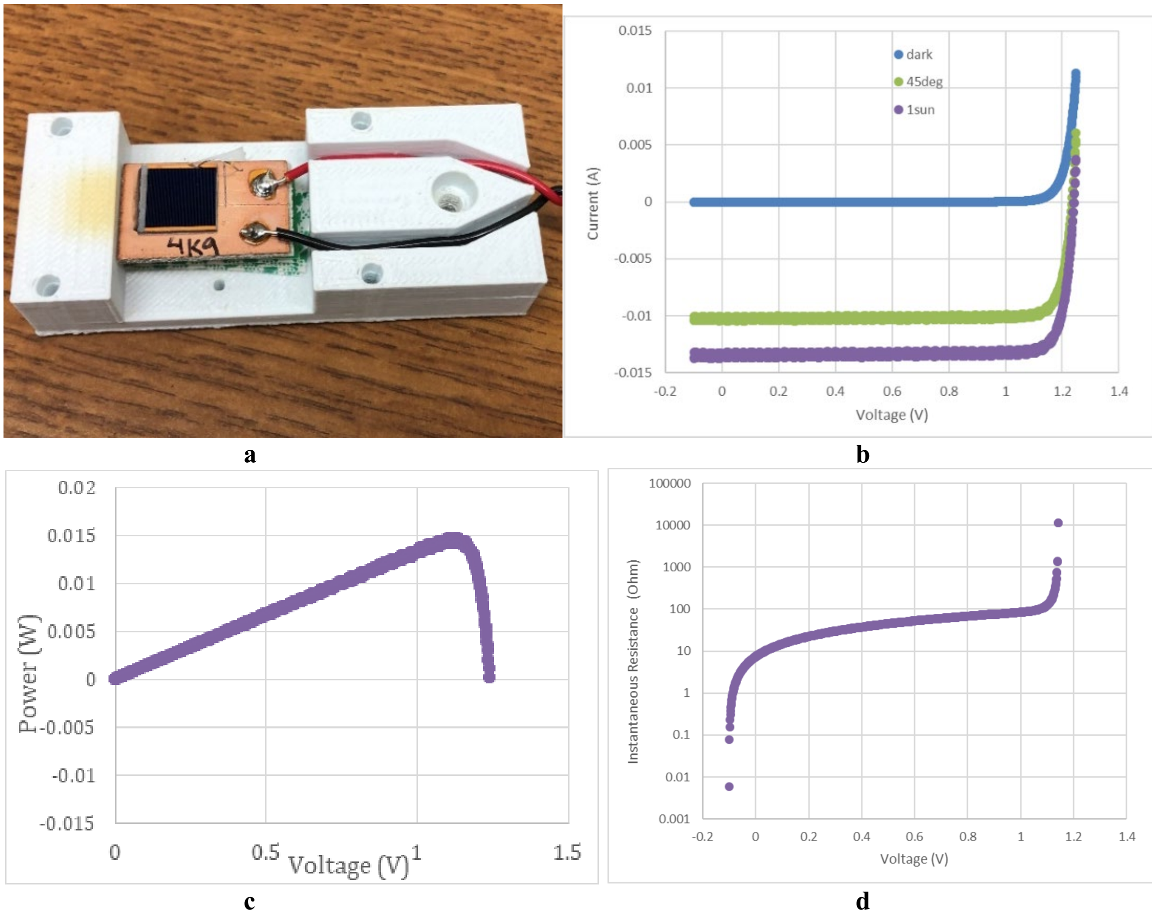
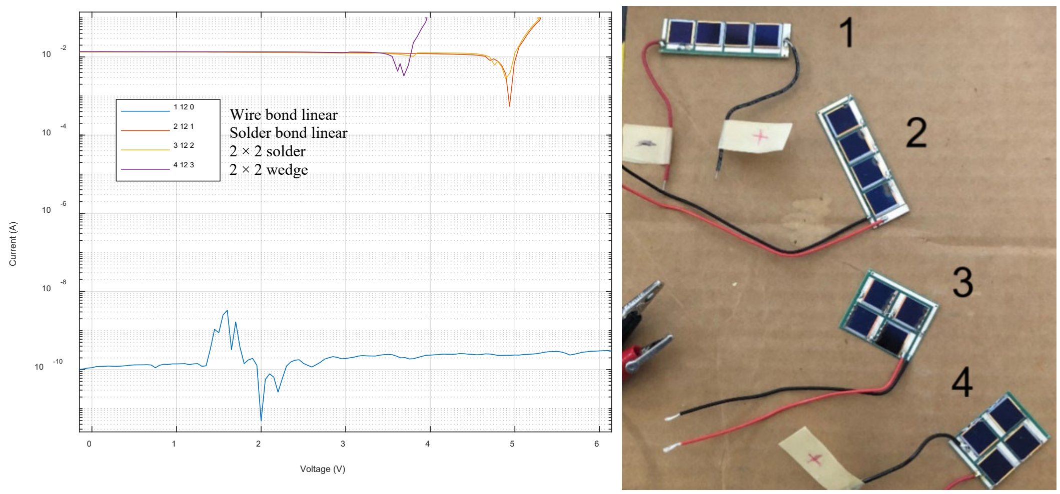


Fig. 8 a) Packaged InGaP 1 cm^2 PV 4K9. b) IV curves showing the variation of InGaP cell output for dark current, 45° incidence, and 1-sun normal incidence illumination, 100 pA, 11.2 mA, and 13.7 mA, respectively. c) The MPP for 1-sun normal incidence is 15 mW at 1.2 Voc. d) The instantaneous resistance at the MPP is 100 Ω.

3.2 Performance of Assembled Linear and 2 × 2 Arrays

While each individual InGaP device can produce tens of μW of power from indoor lighting, arrays of these chips can produce hundreds of μW. To demonstrate these higher power capabilities, four InGaP cells were mounted to a wafer board with silver epoxy and wire bonded in a series configuration to form an array. A linear mounted array version is shown in Fig. 6b. Two arrays were packaged using wire bonding on a 4 × 1 array and wedge bonding on a 2 × 2 array. Since each device outputs approximately 60 μW under room light, a quad array would ideally have an output power around 240 μW. Given that the devices are mounted in series, the electrical current output of each device has to match (conservation of charge) and the voltages must add up. Our expectation is that the quad array should have an output current of around 60 μA at 4 V when exposed to indoor lighting.

The measured values of single cell InGaP devices resulted in 1.1 V, 13 mA electrical output (Fig. 8b and 8d). The series connected array of InGaP cells would be expected to produce 4.4 V and 13 mA when illuminated by 1-sun intensity producing 57 mW at MPP. The measured result of the four arrays fabricated are shown in Fig. 9. Two of the four arrays (the 2 × 2 solder bond and the linear solder bond) operate as expected. The 2 × 2 wedge-bond array produces the full current but a reduced Voc. This result indicates that one of the cells is not contributing to the voltage output and may be shorted. The wire-bonded linear device produces an open circuit output and has likely lost some of the wire bond connections (there were originally three connections on each cell).



a b

Fig. 9 a) IV curves of InGaP quad array in direct sun; (13 mA, 95 mW Pelec wire bond (device 1-blue) needs replacement of ball bonds that became open circuit. The 2 × 2 wedge bond (device 4-purple) shows reduced Voc from one poor performing cell. b) 1 – the linear array wire bond packaged); 2 – the linear array solder connection; 3 – the 2 × 2 array solder connection; and 4 – the wedge bond arrays.

4. Conclusions

We fabricated four series voltage arrays of InGaP cells producing 50 mW in 4 cm^2. The ball bond connections (using 0.7-mil gold wire) are the most mechanically sensitive connections and should be protected with a layer of epoxy to increase reliable mechanical connection. The wedge-bond connections (using 10-mil Ti wire) comprise wire length approximately 50-mil long on the contact bar of the PV. The process of wedge bonding can put pressure on the PV contact and degrade the PV even if great care is taken during fabrication. Soldering 100-µm silver wire onto the InGaP bar/surface contacts proved the most successful; however, the process takes much practice to avoid damage from mechanical pressure and heat damage to the local area of the PV contact bar. We have yet to try oven bump bonding techniques. With a properly designed wafer board, the bottom side (positive) contact of the InGaP can be made while the top side (negative) contact can be implemented in one heating operation.

Advancements in semiconductor technology have allowed for higher efficiency devices, and development of real-world applications using these devices are now feasible. However, packaging techniques must be streamlined for these developments to progress. Each step of the process (testing, mounting, wire bonding, reservoir creation) has its own unique challenges. Arraying of efficient BV/PV devices presents an opportunity to produce hundreds of $\mu W/cm^2$ (indoor) to tens of mW/cm^2 (outdoor) of power, but there are obstacles. Attempts to create a quad array were successful, but wire bonding continues to be the most precise and delicate task. Soldering was the most reliable task with a quick skilled hand avoiding undue mechanical pressure and local heating. Wire bonding and wedge bonding have required reworking to operate at full capacity, such as placing multiple bonds and reinforcing with epoxy. The fabricated array produced the approximately 240 μW indoors and 57 mW outdoors, while future goals include building larger-scale arrays to produce hundreds of mW of power and experimenting with radioisotope packaging to find the most energy efficient methods.

5. References

1. US Energy Information Administration; n.d. [accessed 2022 May 3]. https://www.eia.gov/international/overview/country/USA.

2. United States Geological Survey; 2003 [accessed 2022 May 3]. http://www.usgs.gov.

3. Stan M, Aiken D, Cho B, Cornfeld A, Diaz J, et al. Evolution of the high efficiency triple junction solar cell for space power. Proceedings of the 2008 33rd IEEE Photovoltaic Specialists Conference; 2008. p. 1–6. doi: 10.1109/PVSC.2008.4922709.

4. Shahrjerdi D, Bedell SW, Ebert C, Bayram C, Hekmatshoar B, et al. High-efficiency thin-film InGaP/InGaAs/Ge tandem solar cells enabled by controlled spalling technology. Appl Phys Lett. 2012;100:053901. doi: 10.1063/1.3681397.

5. OpenStax, Chemistry. OpenStax CNX; 2016 Jun 20 [accessed 2022 May 3]. https://opentextbc.ca/chemistry/chapter/21-3-radioactive-decay/.

6. Revankar ST, Adams TE. Advances in betavoltaic power sources. J of Energy and Power Sources. 2014 Dec;1(6):321–329.

7. Tompkins RP, Hogan K, Pullen C, Kierzewski I, Kelley S, Doumbia M, Smith BA, Shahedipour-Sandvik S, Litz M. Comparison of planar vs. textured silicon carbide (SiC) betavoltaic devices. Army Research Laboratory (US); 2020 Feb. Report No.: ARL-TR-8910.

8. Russo J, Litz M, Ray II W, Rosen GM, Bigio DI, Fazio R. Development of tritiated nitroxide for nuclear battery. Applied Radiation and Isotopes: Including Data, Instrumentation and Methods for use in Agriculture, Industry and Medicine. 2017;125:66–73.

9. Spencer MG, Alam T. High power direct energy conversion by nuclear batteries. Appl Phys Rev. 2019;6(3):031305.

10. Olsen LC. Betavoltaic energy conversion. Energy Conversion. 1973;13:117–127.

11. Kurmanbay A, Baktybekov K, Sakhanov K, Syzdykov A, Mukhamediyev A. Optimization of series-parallel connection of PV array to mitigate negative influence of partial shading conditions. IOP Conf Ser: Mater Sci Eng. 2020;868 012001.

12. Wire Bonding – IC Assembly Servies. QPtechnologies.com, QP Technologies; 2021 Mar 10 [accessed 2022 May 3]. www.qptechnologies.com/services /ic-assembly/wire-bonding/.

13. Wire Bonding. Palomertechnologies.com, Palomar Technologies; 2021 [accessed 2022 May 3]. www.palomartechnologies.com/processes/ wire-bonding/aluminum.

Appendix. Fabrication and Testing Procedures

A.1 InGaP Wafer Testing Details

This testing involved the use of a Raspberry Pi computer, a 3450 Keithley source meter, and a probe station. Code was written for the Raspberry Pi to operate the source meter, which applied a voltage function to the InGaP chip and recorded the output current to a flash drive. The device executed a sweep from –5 to +5 V at intervals of 0.05 V until the current reached the 50-mA limit (set as the current compliance) or the voltage reached 5 V. The probe station consisted of a copper sheet and a probe tip, the copper sheet serving as the positive and the probe tip serving as the negative. The devices were laid on the sheet with their back contacts touching the copper, and the probe tip was carefully placed on the top gold contact bar for each chip. During data collection, the number of the InGaP chips being tested and the time of testing were written down to identify them in the data file, as well as the Isc to get an initial idea of whether they were behaving as diodes or resistors.

A.2 Instructions on Mounting InGaP and Reservoir

Materials:

- A diamond tipped scribe
- A Sharpie marker
- A multimeter with two wires
- Two-part Silver epoxy
- UV-cured resin
- Lab spatula
- Dental pick
- Isopropyl alcohol
- Tissues
- Soldering station
- Two wire leads
- A 1.0 × 1.5-inch copper board

1) Begin with the copper board and using the diamond scribe, carve out a divot in the bottom right as in Fig. A-1.

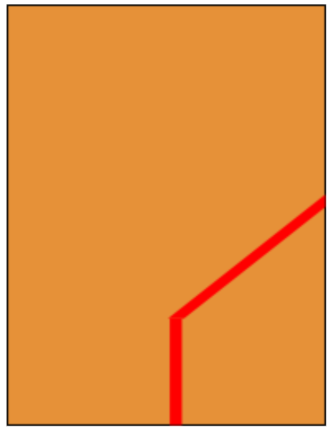


Fig. A-1 The red line indicates the divot that should be carved into the board

2) Using a multimeter, test the board for continuity by placing one probe to the left of the groove and the other probe to the right. If the multimeter indicates that there is a short, try to find where you may have missed the copper foil or check to see if any dirt got in the groove. Run the scribe through the groove and clean out anything that it catches on.

   Note: The most likely spot for a short to happen is the end of the groove where it meets the edge of the coupon. Ensure this is scraped out a little bit down the side of the coupon.

3) Epoxying semiconductor chip to board
   a) Using isopropyl alcohol, clean off the surface of the copper coupon.
   b) Select a semiconductor chip and note the number on the back.
   c) Write the number of the semiconductor chip on the back of the copper coupon.
   d) Open the silver epoxy and using the lab spatula, stir it until the light and dark components are mixed into one color.
   e) Take the spatula and using the epoxy still stuck to it, lay down a small drop onto the coupon with size and location shown by the dot in Fig. A-2.

      Note: Be careful not to apply too much epoxy, as it will leak around the sides and short the semiconductor chip. This is a very good adhesive and conductor so a little goes a long way.

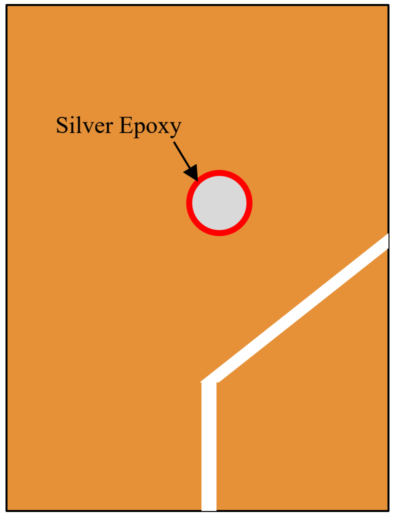


Fig. A-2 The silver circle outlined in red marks the size and location of the silver epoxy

f) Lay the chip overtop of the epoxy in the orientation shown in Fig. A-3, with the gold contact bars perpendicular to the groove. Press down gently until it is flush with the board.

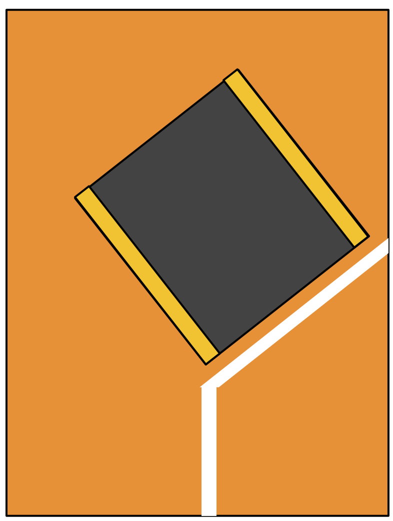


Fig. A-3 The chip is oriented so that the contact bars are perpendicular to the divot

4) Squeeze the resin out along the edge of the chip as shown in Fig. A-4. The line of resin should be as tall as the chip and as long as its edge. UV-cure the resin and check that it is dry.

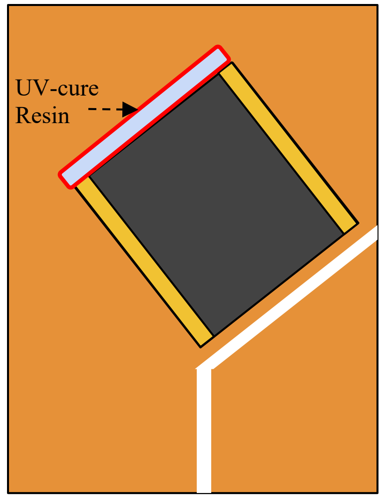


Fig. A-4 The location and width of the UV-cured resin is outlined in red

5) Place the device directly beneath a heat lamp, 1 foot from the source, for three days.

   Note: The lamp must remain on until the end of the three days or the epoxy will not cure. You can use your hand to feel whether the heat lamp is providing enough heat.

6) Make two bonds in the manner below, shown in Fig. A-5 by the red lines, one to each contact bar. For better connectivity, make multiple bonds to each contact bar.

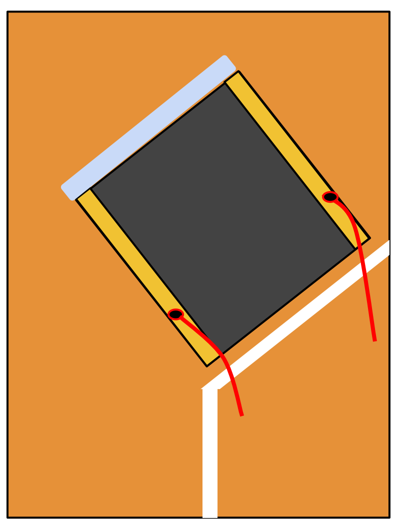


Fig. A-5 The red lines designate length and location for the two wire bonds

7) Since wire bonds could become unbonded with the slightest touch, they may need reinforcement for the tests that will eventually be conducted on the device.

   a) Prepare the silver epoxy with a spatula.

   b) Under a microscope, locate the ball bonds on the device.

   c) Take a dental pick and apply a very light drop of epoxy to each bond. Be careful not to touch the wire with the pick, or the bond may break off.

   d) Be careful not to let any epoxy run off the contact onto the semiconductor surface.

   e) Place the device under a heat lamp for a few hours until the epoxy is solidified.

8) Solder one black and one red wire to the board as shown in Fig. A-6.

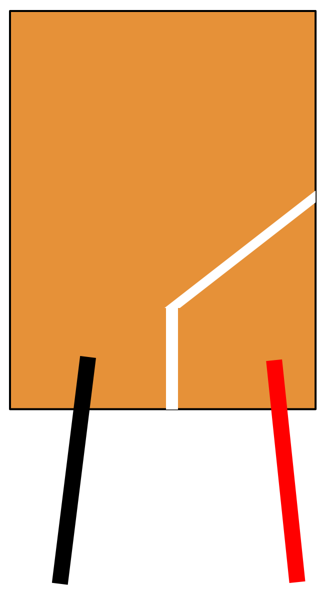


Fig. A-6 The red and black wires are placed in the locations shown and soldered at the point where each wire meets the board

Your final product should look like Fig. A-7.

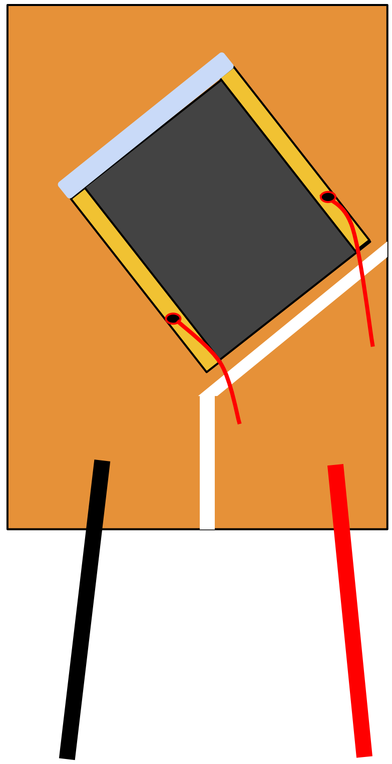


Fig. A-7 The final product includes all of the components outlined in these directions

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
AV	alphavoltaic
BV	betavoltaic
EHP	electron-hole pair
EQE	external quantum efficiency
FF	fill factor
InGaP	indium gallium phosphide
IV	current-voltage
LED	light-emitting diode
MPP	maximum power point
PV	photovoltaic
Voc	open-circuit voltage

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