LM-04K064
August 24, 2004

Micron-gap ThermoPhotoVoltaics (MTPV)

R DiMatteo, P Greiff, D Seltzer, D Meaulenberg, E Brown, E Carlen, K Kaiser, S Finberg, H Ngyyen, J Azarkevich, P Baldasaro, J Beausang, L Danielson, M Dashiell, D DePoy, H Ehsani, W Topper, K Rahner, R Siergiej

Micron-gap ThermoPhotoVoltiacs (MTPV)

R. DiMatteo, P. Greiff, D. Seltzer, D. Meulenberg, E. Brown, E. Carlen, K. Kaiser, S. Finberg, H. Nguyen

The Charles Stark Draper Laboratory, Inc., Cambridge, MA

J. Azarkevich, P. Baldasaro, J. Beausang, L. Danielson, M. Dashiell, D. DePoy, H. Ehsani, W. Topper, K. Rahner

Lockheed Martin, Schenectady, NY

R. Siergiej

Bechtel Bettis Inc., West Mifflin, PA

Abstract. This paper discusses advances made in the field of Micron-gap ThermoPhotoVoltaics (MTPV). Initial modeling has shown that MTPV may enable significant performance improvements relative to conventional far field TPV. These performance improvements include up to a 10x increase in power density, 30% to 35% fractional increase in conversion efficiency, or alternatively, reduced radiator temperature requirements to as low as 550°C. Recent experimental efforts aimed at supporting these predictions have successfully demonstrated that early current and voltage enhancements could be done repeatedly and at higher temperatures. More importantly, these efforts indicated that no unknown energy transfer process occurs reducing the potential utility of MTPV. Progress has been made by running tests with at least one of the following characteristics relative to the MTPV results reported in 2001:

- Tests at over twice the temperature (900°C).
- Tests at 50% smaller gaps (0.12 μm)
- Tests with emitter areas from 4 to 100 times larger (16 mm^2 to 4 cm^2).
- Tests with over 20x reduction in parasitic spacer heat flow.

Remaining fundamental challenges to realizing these improvements relative to the recent breakthroughs in conventional far field TPV include reengineering the photovoltaic (PV) diode, filter, and emitter system for MTPV and engineering devices and systems that can achieve submicron vacuum gaps between surfaces with large temperature differences.

INTRODUCTION

In far field TPV, radiation heat transfer is limited by the density of states in vacuum to σT^4. However, in MTPV, the small submicron gap enables energy within the hot radiator to "evanescently couple" or "tunnel" directly to the TPV diode, resulting in a higher limit of $n^2\sigma T^4$ for dielectrics of index n. Radiation heat transfer from the hot radiator to the TPV diode can be increased significantly, resulting in the potential for large gains in electrical output power density. Recent work has probed this and related effects. [1-3]

This effect is also explained by the well-known wax prism experiment that demonstrates the evanescent coupling depicted in Figure 1. Light enters the top prism and is totally internally reflected at the bottom surface of the top prism when the spacing between the two prisms is greater than the wavelength of the incident light. However, when the spacing between the prisms is much less than the wavelength of the incident light, the light is NOT totally internally reflected at the bottom surface of the top prism. Instead, it is evanescently coupled or "tunnels" across the gap and is transmitted through the bottom prism. This same principle applies to energy that is internal to the TPV radiator. MTPV enhancement is limited to n^2 of the lowest index of refraction material and in general will depend on the wavelength dependent nature of the index.

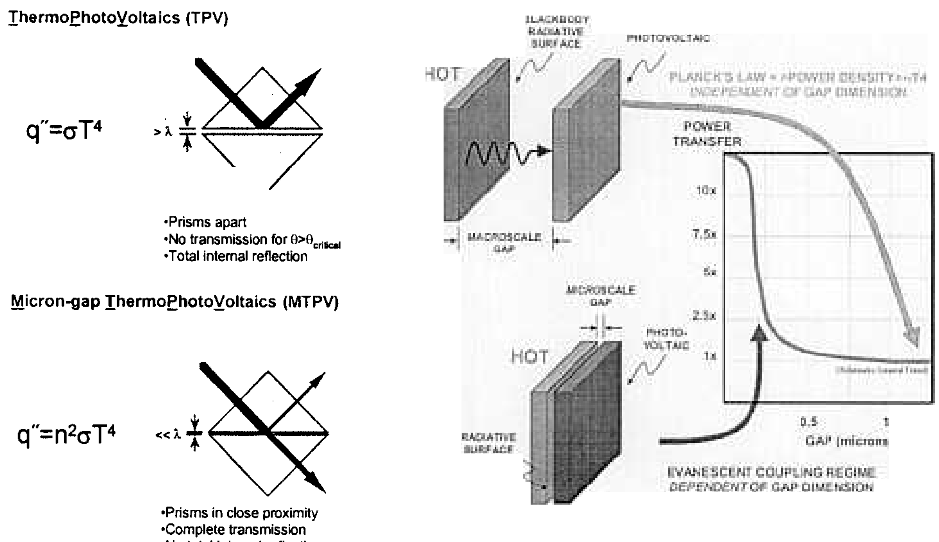


Figure MTPV Background. Potential for large gains in power density from close spacing.

The experimental apparatus and test results for the initial close space test (done under the Defense Advanced Research Projects Agency (DARPA) palm power program) are shown in Figure 2. This test was performed at 400°C, 0.2-µm gap, with conventional spacers, and was made using an 0.55 eV InGaAs diode fabricated by NASA. The up/down test confirmed the presence of the enhancement of Isc and Voc. This paper reviews progress made since this work was done.

RECENT WORK

Figure 3 shows the pedestal test fixture used to measure heat transfer from the radiator to the PV diode. The ΔT down the pedestal gives heat absorbed by the PV. This test enables the direct measurement of efficiency.

Figure 4 shows larger area heater chips fabricated by connecting four smaller 2 mm x 2 mm heater chips into a 2 x 2 array. Larger heater chips enable higher power outputs and more accurate heat flow measurements.

Another important development over the past year is the ability to measure the full IV curve, as shown in Figure 5. This enables the experimental determination of the fill factor and max power output from the PV cell. Previous efficiency estimates were made by measuring Isc and Voc and estimating the fill factor.

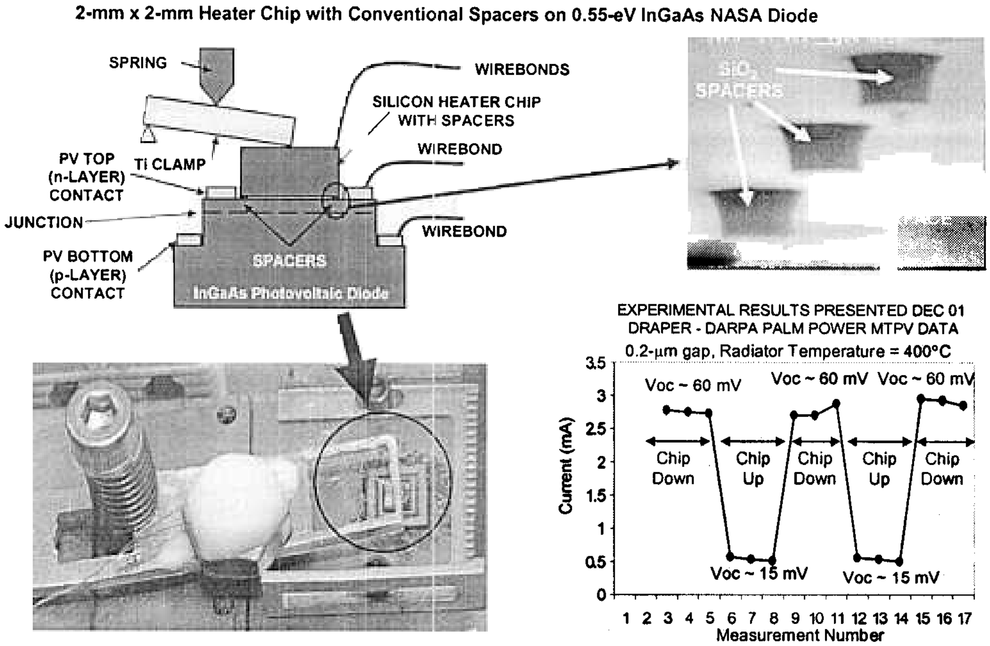


Figure 2. MTPV Status in 12/01. First experimental results showing Isc and Voc enhancement.

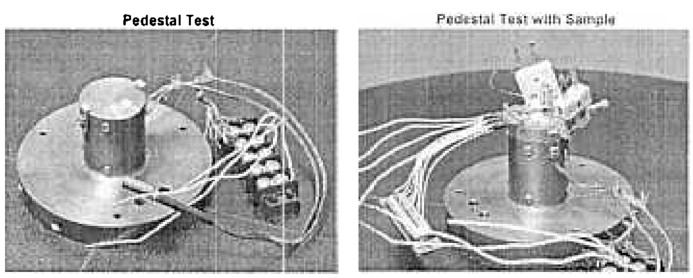


Figure 3. Pedestal test enables measurement of heat absorption.

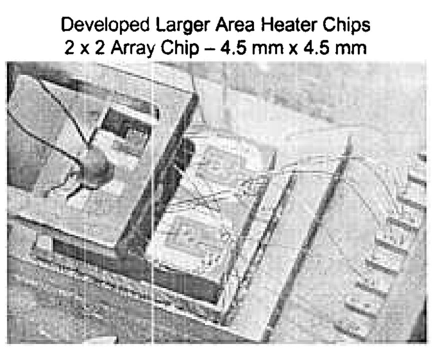


Figure 4. Larger area heater chips 2 x 2 array chip–4.5 mm x 4.5 mm. Larger area heater chips enable higher power output and more accurate heat flow measurements.

Developing polishing techniques has been key to providing the surface flatness required for MTPV. White light interferometer measurements (ZYGO) show that polishing reduced the bow of an inverted InGaAs diode from ~0.4 μm to ~0.05 μm, as shown in Figure 6.

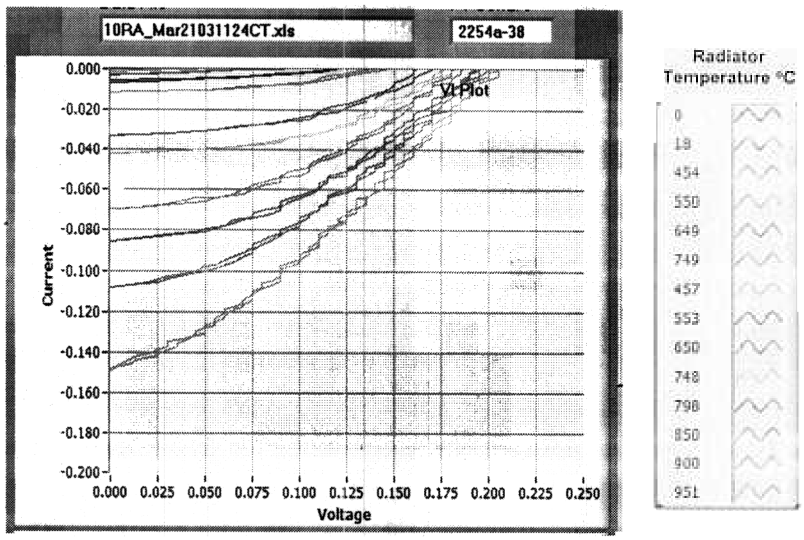


Figure 5. Developed diode IV measurement capability. Full IV curve measurement enables the determination of fill factor and P_{max}.

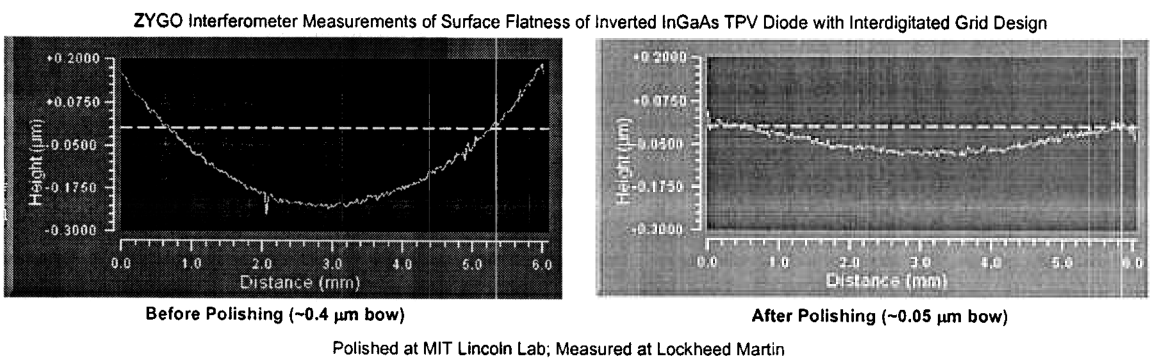


Figure 6. Developed polishing technique. Polishing resulted in extremely flat surface required for MTPV.

Several diode designs, shown in Figure 7, were fabricated for MTPV experimentation. Diode design evolution has resulted in diodes with higher current-carrying capability (higher fill factors at high currents), scalable designs, and designs with back surface reflector/low index reflector (BSR/LIR) spectral control. More work is necessary to increase MTPV spectral control and fill factor performance to levels currently being obtained in far field TPV.

The diodes presented in Figure 7 have been fabricated and tested in an up/down MTPV test. Figure 8 shows the results of this testing as a function of radiator temperature. An electrical output power enhancement was seen for each of the diode architectures confirming the MTPV effect. The actual magnitude of the photogenerated current enhancement for these tests is uncertain due to series resistance (diode and test setup), shunt resistance, and variation of diode temperature. For example, the quaternary diode was measured using a 2-point measurement. In this type of measurement, the series resistance of the leads (wires) caused the enhancement to decrease as temperature increases due to high I^2R losses. The InGaAs diodes were measured using a 4-point measurement that eliminates this problem. However, the gridless diode (NASA) has high series resistance, which also causes a decrease in fill factor as current is increased and results in a lower enhancement as radiator temperature is increased. The inverted/interdigitated diode has low series resistance and was measured using a 4-point measurement, and the enhancement does not decrease as radiator temperature increases. However, this diode has a low shunt resistance. This is believed to be the cause of the very high output enhancement, especially at the lower radiator temperature. More work is necessary in order to determine the actual enhancement of photogenerated current.

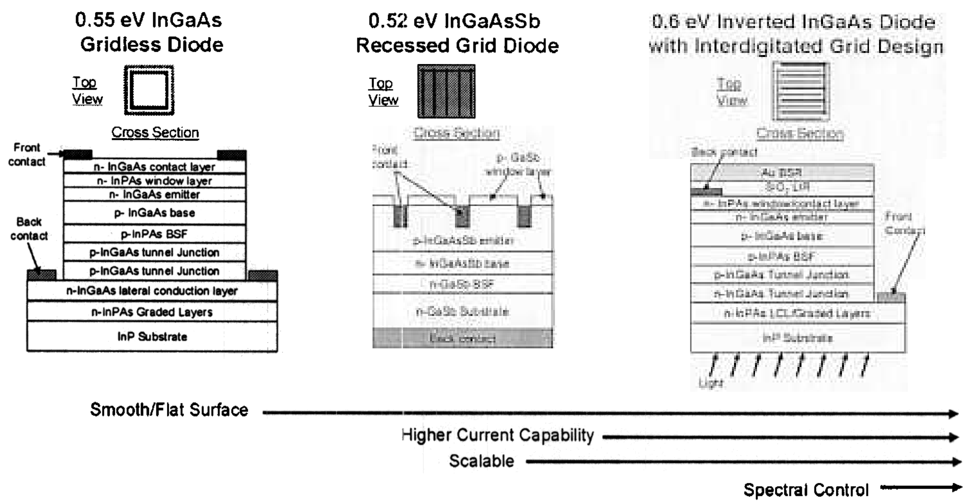


Figure 7. MTPV diode design evolution. Progress being made on MTPV diode design.

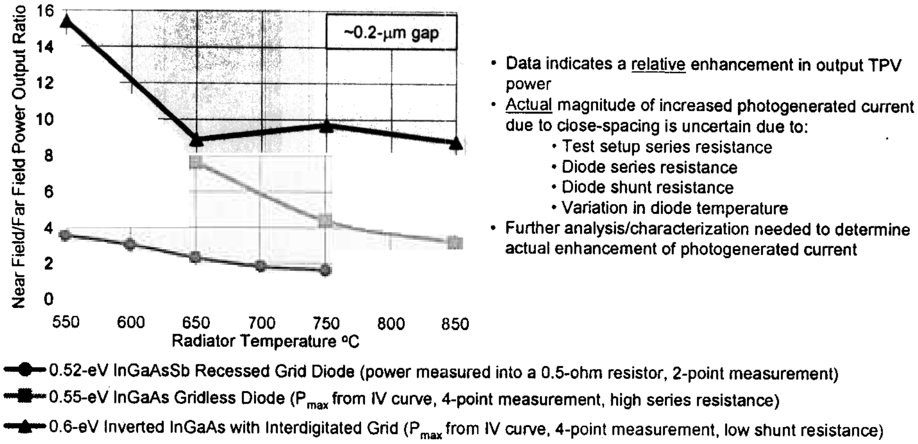


Figure 8. Confirmatory measurements of MTPV effect/testing at higher radiator temperature. Demonstrated enhancement with multiple diode architectures and at higher radiator temperatures.

Figure 9 shows that heat absorption enhancement is of the same order of magnitude as diode electrical output power enhancement. While this indicates that there is no large unexpected heat flow, we know that conductive heat flow through conventional spacers is a problem.

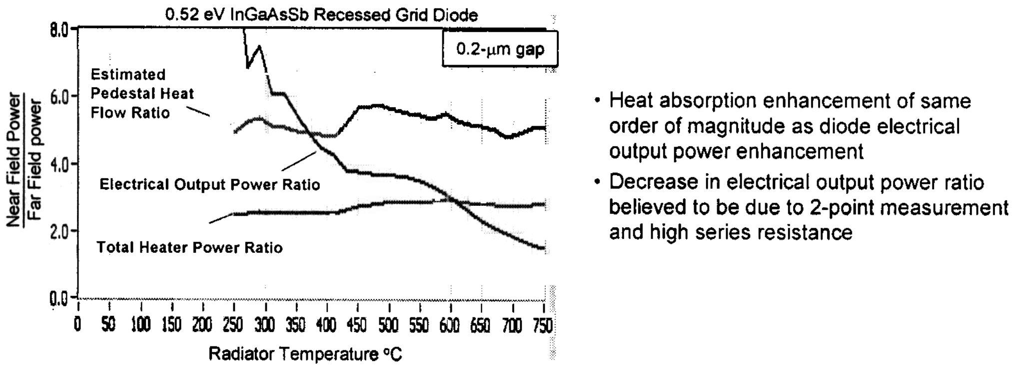


Figure 9. Comparable enhancement of electrical output power and heat flow. No order of magnitude unknown heat flow is present.

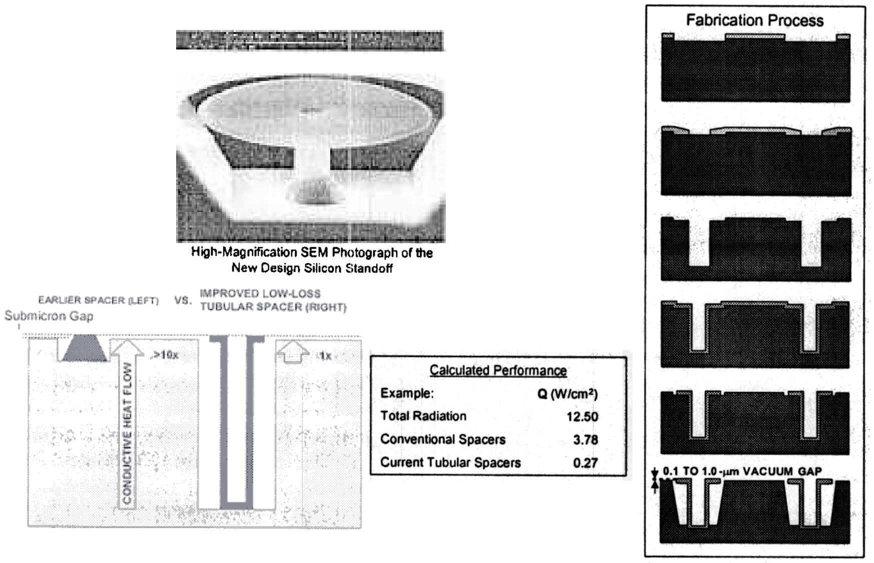


Figure 10. Developed MEMS tubular spacers. Parasitic heat conduction through tabular spacers is predicted to be less than 3% of total radiation.

Previous work with conventional heater chip spacers showed unacceptably large conductive heat transfer through the spacers. Tubular spacers have been developed that significantly reduce this parasitic heat transfer. The tubular spacers are predicted to reduce heat conduction by more than 10x compared with previous conventional spacers. This is mainly due to the increased length of the spacers ($Q_{conduction} = (kA/L)\cdot\Delta T$, where the symbols have their usual meaning). Analysis shows that tubular spacers shown in Figure 10 reduce parasitic conduction heat flow to less than 3% of the total heat transferred by radiation.

This calculation assumes a TPV diode with spectral control equivalent to today's far field results and a 5x enhancement. Larger enhancements or poorer spectral control would result in a smaller fraction of heat transferred by conduction (i.e., conduction would stay the same, but radiation heat transfer would increase).

In order to isolate the tubular spacer heat flow from the radiative heat flow, we needed to render the radiative heat flow constant while having the spacers both in contact with the cold side and then not in contact. The MTPV tubular heater chips were etched back to create the 4-µm (far field) gap as shown in Figure 11. A 2 x 2 array heater chip (4.5 x 4.5 mm in size) shown earlier was used with 16 tubular heater spacers. Pedestal heat flow measurements were made with the spacers in contact, and then the heater chip was raised so that the spacers were not touching, thus eliminating conductive heat flow through them. This test was performed at 640°C and 780°C, and conductive heat flows at or less than 120 mW were measured.

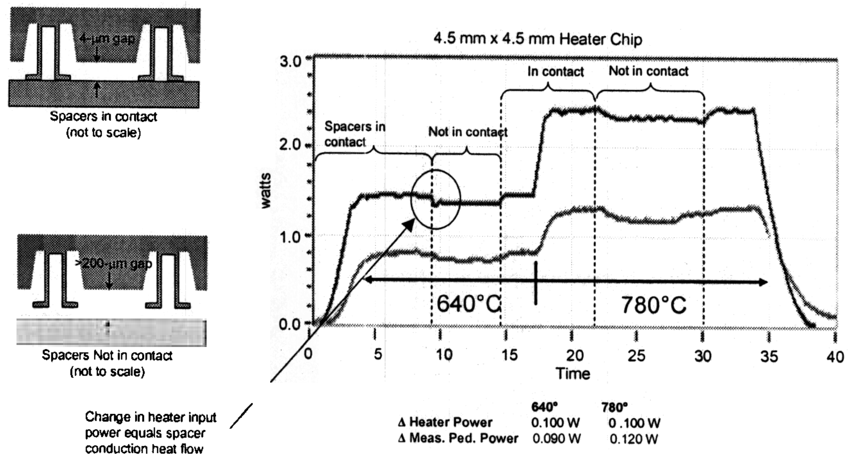


Figure 11. MEMS tubular spacer far field heat flow test. Measured tubular spacer heat flow indicates low parasitic heat transfer.

Tubular spacers are compliant (compressible) and enable varying the microgap by varying the force applied to the heater chip (i.e., applying force to the heater chip compresses the tubular spacers and reduces the gap). Figure 12 shows results from a preliminary experiment demonstrating this effect. The same heater chip was used and was moved from a 0.35-μm gap to a 0.12-μm gap and back to a 0.35-μm gap.

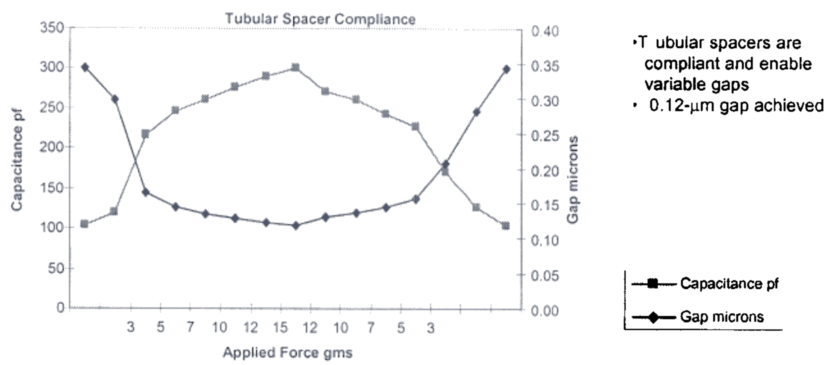


Figure 12. Developed variable gap capability/achieved smaller gap. May enable dynamic gap control.

One potential design issue for MTPV is maintaining high diode fill factors at the higher photogenerated current levels. As depicted in Figure 13, this design issue can be mitigated by redesigning the diode architecture to achieve a lower device series resistance. In order to maintain an increase in device fill factor as the illumination level increases (as would be seen in a diode with zero series resistance), the series resistance must be reduced by an amount approximately equal to the increase in short circuit current. Reducing the device series resistance can be accomplished by increasing carrier densities, changing layer thickness (thicker for lateral conduction paths) and/or reducing the conduction path length. The first two of these series resistance reduction strategies will cause increased free carrier absorption, reduced long wavelength reflectivity, and reduced spectral performance. Reducing the diode width in a MIM would provide lower lateral conduction layer (LCL) series resistance without a decrement in spectral performance. However, reducing the diode width reduces active area.

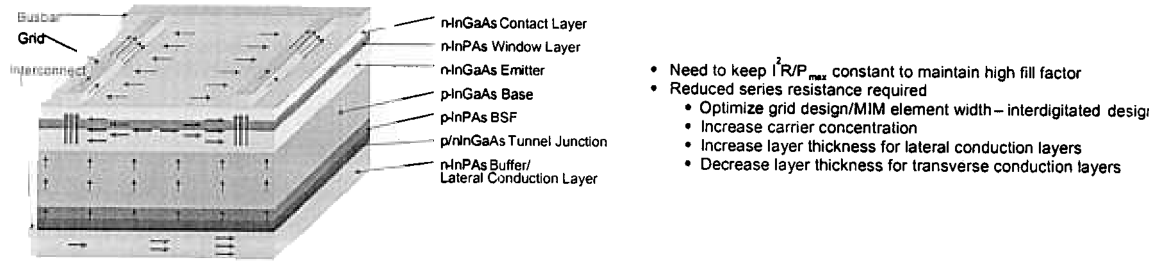


Figure 13. Current flow in standard far-field InGaAs MIM structure. Need to Maintain Fill Factor with up to 10X I_{sc} from MTPV.

Since the traditional tandem filter concept will not work in an MTPV configuration (due to the presence of low index of refraction materials in the interference filter), a BSR will be necessary to provide spectral control for enhanced TPV concepts. As shown in Figure 14, a BSR allows above-bandgap photons to be absorbed by the diode, while below bandgap photons pass through the diode and are reflected back to the radiator by a reflector located on the back surface of the diode. The full angular dispersion of photons for MTPV offers two conceptual advantages in spectral control compared with far-field BSR configurations: (a) the use of an LIR that provides total internal reflection of photons outside the cone of acceptance, and (b) greater tolerance to diffuse reflection sources.

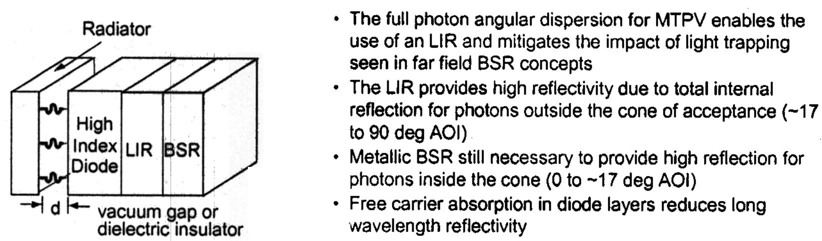
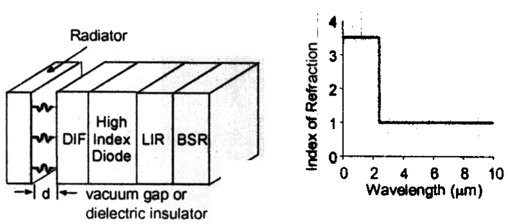


Figure 14. Low index reflector (LIR) back surface reflector (BSR) concept. Trade-off between diode and spectral performance with BSR spectral control.

Doping is necessary in the various diode layers (cap, window, emitter, base, back surface field, and lateral conduction layers) to provide the rectifying p-n junction, reduce series resistance in current-carrying layers, enable ohmic contacts, decrease surface recombination, etc.... Doping in the diode layers, however, decreases spectral performance by reducing long wavelength reflection due to free carrier absorption. Therefore, optimizing diode architecture when relying on a BSR for spectral control is complicated by a performance trade-off that exists between diode efficiency and spectral efficiency as diode layer doping levels are adjusted. The desire to have a front surface filter in an MTPV configuration that mitigates long wavelength free carrier absorption in the diode layers has led to a new spectral control concept for MTPV configurations. In the dispersive index filter (DIF) concept (Figure 15), a single layer located on the front of the TPV device provides spectral control wavelength selectivity by the index of refraction dispersion of the DIF material. The DIF provides front surface reflection of photons due to total internal reflection at wavelengths where the index of refraction is low, and does not inhibit n^2 photon flux enhancement where the index of refraction is high. For low index of refraction spectral regions, the DIF essentially acts as a LIR that is located on the front of the TPV device instead of on the back of the device. The ideal index of refraction versus wavelength characteristic would provide a very high index of refraction in the above-bandgap spectral region, a very low index of refraction in the below-bandgap region, and a very sharp transition from high index to low index. The DIF would also work as a coating on the radiating surface or as selective radiator. Heavily doped semiconductors may be good DIF candidates.



- DIF is similar to LIR but between diode and radiator
- Cold side and/or hot side
- The DIF provides high enhancement of GOOD photons and low enhancement of BAD photons
- Reduces concern for free carrier absorption and diode/spectral control trade-off
- Metallic BSR still necessary to provide high reflection for BAD photons inside the cone

Figure 15. DIF concept. DIF may enable independent optimization of diode and spectral performance for MTPV.

CONCLUSION

Power densities in excess of far field values are physically possible and aspects of this have become well understood. Devices have been built and tested to demonstrate some of these effects. New mechanisms need to be explored further. Practical devices with sufficient performance, lifetime, and durability are being developed.

REFERENCES

1. Bierley, J.M., and Gopinath, A., A parametric design study of InGaAs micro-thermophotovoltiac cells coupled with various emitters at near and far spacing, TPV 5, p.259
2. Baldasaro, P.F. and Fourspring P.M., Improved Thermophotovoltaic (TPV) Performance Using Dielectric Photon Concentrations (DPC), STAIFF, February 2003
3. Narayanaswamy, A. and Chen, G., Surface modes for near field thermophotovoltaics, Applied Physics Letters, v.82, n.20, May 19, 2003, p.3544
4. Siergiej, R.R., et. al., 20% Efficient InGaAs/InPAs Thermophotovoltaic Cells, TPV 5, p.414
5. Wernsman, B., et. al., Greater Than 20% Radiant Heat Conversion Efficiency of a Thermophotovoltaic Radiator/Module System Using Reflective Spectral Control, IEEE Transactions of Electron Devices, Vol. 51, No. 3, March 2004, p.512