LM-02K141
December 18, 2002

GaInAsSb/A1GaAsSb/GaSb Thermophotovoltaic Devices With an Internal Back-Surface Reflector Formed by Wafer Bonding

C.A. Wang, R.K. Huang, D.A. Shiau, M.K. Connors, P.G. Murphy, P.W. O'Brien,
A.C. Anderson, D.M. DePoy, G. Nichols, M.N. Palmasiano

LM02K141

GaInAsSb/AlGaAsSb/GaSb Thermophotovoltaic Devices with an Internal Back-Surface Reflector Formed by Wafer Bonding*

C.A. Wang, R.K. Huang, D.A. Shiau, M.K. Connors, P.G. Murphy, P.W. O'Brien, A. C. Anderson

Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420

D.M. DePoy, G. Nichols

Lockheed Martin Corporation, Schenectady, NY 12301

M.N. Palmasiano

Bechtel Bettis, Inc., West Mifflin, PA 15122

ABSTRACT

A novel implementation for GaInAsSb/AlGaAsSb/GaSb TPV cells with an internal back-surface reflector (BSR) formed by wafer bonding to GaAs is demonstrated. The SiO_x/Ti/Au internal BSR enhances optical absorption within the device, while the dielectric layer provides electrical isolation. This configuration has the potential to improve TPV device performance; is compatible with monolithic series-interconnection of TPV cells for building voltage; and can mitigate the requirements of filters used for front-surface spectral control. At a short-circuit density of 0.4 A/cm^2, the open-circuit voltage of a single TPV cell is 0.2 V, compared to 0.37 and 1.8 V for 2- and 10-junction series-interconnected TPV cells, respectively.

---

*This work was sponsored by the Department of Energy under AF Contract No. F19628-00-C-0002. The opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

GaInAsSb-based thermophotovoltaic (TPV) devices are being developed for high-efficiency TPV systems that generate electricity from thermal radiation.[1,2] The GaSb-based III-V semiconductor alloys are attractive for TPV devices since the bandgap of the active layer can be independently adjusted over a wide energy range (0.28 to 0.72 eV) while maintaining lattice-matching to the GaSb substrate. Consequently, the bandgap of the TPV cell can be optimized for a given thermal radiator temperature.[3] Alternative materials based on lattice-mismatched InGaAs/InP are also being studied, and advanced TPV cell designs, which include a back-surface reflector (BSR) and series connection of cells in a monolithically interconnected module (MIM), are being developed to improve TPV system performance.[4-8] The BSR, which was deposited on the backside of the substrate, was used to provide both spectral control of below bandgap photons and device improvement through the increased probability of above bandgap photons that are not absorbed in the first pass to be reflected back into the active layer for second-pass absorption. Furthermore, since the epitaxial device structure was grown on a semi-insulating substrate, cells were monolithically series interconnected to build voltage.

Similar approaches for GaSb-based TPV devices are extremely limited since the effectiveness of the BSR is significantly reduced by free-carrier absorption in the GaSb substrate,[9] and the lack of a semi-insulating GaSb substrate[1] precludes series interconnections. Consequently, front-surface spectral control techniques are critical for improving TPV system efficiency.[10] An alternative approach for fabrication of GaInAsSb-based MIMs for voltage building was recently reported using a cell-isolation-diode, and an open circuit voltage V_{oc} of 0.42 V was reported for a 15-junction MIM.[11]

This paper reports a new approach for the implementation of both a BSR and the MIM architecture in GaInAsSb-based TPV cells, shown in Figure 1. The GaInAsSb TPV cell is fabricated with an internal dielectric/Au mirror, which is formed by wafer-bonding the epitaxial layers directly to a GaAs handle wafer. After bonding the epitaxial layers, the GaSb substrate is removed. This concept of wafer-bonding using metal as an adhesive layer is similar to that developed for integration of dissimilar materials[12] and for fabrication of internal mirrors for photovoltaic cells,[13] light emitting diodes,[14] and vertical-cavity surface-emitting lasers.[15] The resulting wafer-bonded GaInAsSb TPV device structure consists of a broad-band high-reflectivity mirror sandwiched between the device layers and the GaAs handle substrate. Consequently, free-carrier absorption due to the GaSb substrate is not an issue and the internal BSR can effectively increase the optical thickness so that active layers can be thinner and photon recycling effects[16] can be enhanced, both of which are advantageous for reducing dark current and increasing open-circuit voltage. In addition, reflection of below bandgap photons back to the radiator can aid in spectral control. Finally, since the epitaxial layers are electrically isolated from the handle substrate by the dielectric layer, TPV cells can be interconnected in series to fabricate MIMs.

GaInAsSb/AlGaAsSb/GaSb TPV device structures were grown lattice matched to 5-cm-diam GaSb substrates by organometallic vapor phase epitaxy.[1,17] Epitaxial layers were grown in a reverse sequence compared to conventional TPV structures[1,17] in order to obtain a p-on-n structure after wafer bonding. In addition, to aid in complete GaSb substrate removal, an InAsSb layer was grown as an etch-stop layer. The as-grown inverted TPV structure consists of the following layers grown on a (001) n-GaSb substrate miscut 6° toward (1-11)B: u-GaSb buffer layer, u-InAsSb etch-stop layer, p-GaSb contact layer, p-AlGaAsSb window layer, p-GaInAsSb emitter layer, n-GaInAsSb base layer, and n-GaSb lateral conduction layer (LCL). Although the InAsSb etch-stop layer is eventually removed during fabrication of wafer-bonded epitaxial TPV structures, it is critical that this layer is also lattice matched to GaSb since the GaInAsSb active layers are grown on top of the InAsSb etch-stop layer.

The inverted TPV structure on the GaSb substrate and the handle semi-insulating GaAs wafer were prepared for bonding with a dielectric/reflector. First, both GaSb and GaAs surfaces were solvent cleaned and etched in HCl and NH_4OH to remove native oxides. The GaSb epitaxial TPV structure was sputter-coated with a three-layer reflector consisting of 200 nm SiO_x/5 nm Ti/2 μm Au, while the GaAs was sputter-coated with 5 nm Ti/2 μm Au. SiO_x not only provides electrical isolation of the epitaxial layers but also increases above band-gap reflectivity. To bond the wafers, the two Au surfaces were placed in contact, and the wafers were heated under vacuum to a temperature of 250 °C and a mechanical pressure of 250 psi was applied. The low bonding temperature is compatible with subsequent wafer processing.

The 5-cm-diam bonded wafer was cut into four quarters for ease of handling and processing, and the GaSb substrate was spin-etched with H_2O_2:H_2O:NaK tartrate tetrahydrate to remove the bulk of the substrate. The remaining GaSb buffer layer and substrate were selectively etched using CrO_3:HF:H_2O until the InAsSb layer was exposed. Finally, the InAsSb etch-stop layer was removed with H_2O_2 saturated with citric acid. The resulting wafer-bonded epitaxy and unbonded control structures, were characterized by high-resolution x-ray diffraction (HRXRD), photoluminescence (PL) at room temperature, and near normal incidence reflectivity. TPV devices were fabricated using standard photolithographic processes and chemical etching to define the TPV cells.[11] In numerous tests, the integrity of the Au-bonded epitaxial layers was maintained throughout all processing steps.

The HRXRD rocking curves for the control GaInAsSb/AlGaAsSb/GaSb TPV device structure on a GaSb substrate and a wafer-bonded GaInAsSb/AlGaAsSb/GaSb TPV structure after removal of the InAsSb etch-stop layer and GaSb buffer layer and substrate are shown in Figures 2a and 2b, respectively. The control structure is well lattice matched to the substrate, and thickness fringes due to the GaSb contact layer are observed. The diffraction intensity is lower for the wafer-bonded TPV device structure because the GaSb substrate has been removed. Thickness fringes from a slightly thicker contact layer are also observed, and the x-ray peak of the wafer-bonded structure is only slightly broadened as a result of residual stress from wafer bonding.

Figure 3 shows 300 K PL spectra for the control and wafer-bonded GaInAsSb TPV structures. Multiple peaks in the PL spectrum of the wafer-bonded sample are due to thin-layer interference effects discussed below. The PL peak intensity of the wafer-bonded epitaxy is over two times greater than that of the control TPV structure. These results suggest that the optical efficiency is enhanced as a result of the internal BSR, and there is negligible material degradation after wafer bonding and substrate removal.

The reflectivity of the wafer-bonded GaInAsSb TPV device structure with and without an anti-reflection (AR) coating on the front surface of the TPV structure is shown in Figure 4. Without the AR coating, resonant absorption is observed across the whole wavelength range due to destructive interference between reflections from the air/GaSb

(R~34%) and GaSb/SiO_x/Ti/Au interfaces. An AR coating designed for above bandgap photons (< 2.5 μm) minimizes resonant absorption. Although this thin layer interference effect will reduce the efficiency of the internal BSR,[18] the overall reflectivity from 2.5 to 15 μm is nearly 78%.

The peak external quantum efficiency of uncoated wafer-bonded GaInAsSb/AlGaAsSb/GaSb TPV devices is 62%, which is comparable to conventional TPV cells.[17] Figure 5 shows results of the short-circuit current density J_{sc} versus open-circuit voltage V_{oc}. The single cell exhibits $V_{oc} \sim 0.2$ V for $J_{sc} = 0.4$ A/cm^2, which is slightly lower compared to previously reported values for conventional TPV cells,[17] and may be due to higher leakage currents in the smaller area cells reported here. For the 2- and 10-junction devices, V_{oc} is 0.37 and 1.8 V, respectively at this same current density, which is indicative of voltage building. The fill factor FF for the 2-junction device is about 51%.

At higher $J_{sc} \sim 2.1$ A/cm^2, V_{oc} is ~ 0.470 and 2.0 V for the 2- and 10-junction devices, respectively. The FF degrades to about 38% for the 2-junction device. There is some saturation of V_{oc} with respect to J_{sc} in the regime of high J_{sc} levels, as shown in Figure 5. The degradation in FF and saturation of the open-circuit voltage at high J_{sc} levels is related to the finite series resistance in the cell-to-cell interconnections. Improved metallization and reduced resistance in the LCL should improve FF.

In conclusion, wafer bonding of epitaxial GaInAsSb/AlGaAsSb/GaSb TPV device structures to GaAs substrates with a high-reflectivity broad-band mirror was achieved, and MIMs with an internal BSR were demonstrated. The structural and optical properties of the wafer-bonded TPV device layers are maintained after fabrication. GaInAsSb TPV devices could be monolithically interconnected in series and voltage-building was demonstrated. These results indicate that this approach is extremely attractive for GaSb-based TPVs fabricated with MIM architecture. The wafer bonding process is not limited to GaAs substrates, and alternative handle substrates can also be considered.

The authors gratefully acknowledge D.R. Calawa, J. Caissie, J.W. Chludzinski, P. Foti, C.T. Harris, S. Hoyt, J.M. Porter, and P.M. Nitishin of MIT Lincoln Laboratory for technical assistance and P. Dutta and I. Bhat for guidance in selective etching. This work was sponsored by the Department of Energy under AF Contract No. F19628-00-C-0002. The opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Government.

REFERENCES

1. C.A. Wang, H.K. Choi, G.W. Charache, IEE Proc.-Optoelectron. **147**, 193 (2000).
2. G.W. Charache, P.F. Baldasaro, L.R. Danielson, D.M. DePoy, M.J. Freeman, C.A. Wang, H.K. Choi, D.Z. Garbuzov, R.U. Martinelli, V. Khalfin, S. Saroop, J.M. Borrego, R.J. Gutmann, J. Appl. Phys. **85**, 2247 (1999).
3. P.F. Baldasaro, J.E.Raynolds, G.W. Charache, D.M.DePoy, C.T. Ballinger, T. Donovan, J.M. Borrego, J. Appl. Phys. **89**, 3319 (2001).
4. J.S. Ward, A. Duda, M.W. Wanlass, J.J. Carapella, X. Wu, R.J. Matson, T.J. Coutts, T. Moriaty, AIP Conf. Proc. 1997, Vol. 401, p. 227.
5. D. M. Wilt, N.S. Fatemi, P.P. Jenkins, V.G. Weizer, R.W. Hoffman, Jr., Raj K. Jain, C.S. Murray, D. Riley, AIP Conf. Proc.1997, Vol. 401, p. 237.
6. N.S. Fatemi, D. M. Wilt, R.W. Hoffman, Jr., M.A. Stan, V.G. Weizer, P.P. Jenkins, O.S. Khan, C.S. Murray, D. Scheiman, D. Brinker, AIP Conf. Proc. 1999, Vol. 460, p. 121.
7. M.W. Wanlass, J.J. Carapella, A.Duda, K. Emery, L. Gedvilas, T. Moriaty, S. Ward, J.D. Webb, X. Wu, AIP Conf. Proc. 1999, Vol. 460, p. 132.
8. R.R. Siergiej, B. Wernsmann, S.A. Derry, R.J. Wehrer, S.D. Link, M.N. Palmisiano, L. Messham, S. Murray, C.S. Murray, F. Newman, J. Hills, D. Taylor, presented at Fifth Conference on Thermophotovoltaic Generation of Electricity, Rome, Italy, September 2002.
9. G.W. Charache, D.M. DePoy, P.F. Baldasaro, B.C. Campbell, AIP Conf. Proc.1996, Vol. 321, p. 339.

10. G.W. Charache, J.L. Egley, D.M. DePoy, L.R. Danielson, M.J. Freeman, R.J. Dziendziel, J.F. Moynihan, P.F. Baldasaro, B.C. Campbell, C.A. Wang, H.K. Choi, G.W. Turner, S.J. Wojtczuk, P. Colter, P. Sharps, M. Timmons, R.E. Fahey, K. Zhang, J. Electron. Mater. **27**, 1038 (1998).
11. M.N. Palmisiano, R.M. Biefeld, J.G. Cederberg, M.J. Hafich, G.M. Peake, presented at Fifth Conference on Thermophotovoltaic Generation of Electricity, Rome, Italy, September 2002.
12. I.-H. Tan, C. Reaves, A. Holmes, Jr., E.L. Hu, J.E. Bowers, S. DenBaars, Electron. Lett. **31**, 588 (1995).
13. F. Omnes, J.-C. Guillaume, G. Nataf, G. Jager-Waldau, P. Vennegues, P. Gibart, IEEE Trans. Electron. Dev. **43**, 1806 (1996).
14. R.H. Horng, D.S. Wuu, S.C. Wei, C.Y. Tseng, M.F. Huang, K.H. Chang, P.H. Liu, K.C. Lin, Appl. Phys. Lett. **75**, 3054 (1999).
15. H.C. Lin, W.H. Wang, K.C. Hsieh, K.Y. Cheng, Electron. Lett. **38**, 516 (2002).
16. J.M. Borrego, S. Saroop, R.J. Gutman, G.W. Charache, T. Donovan, P.F. Baldasaro, C.A.Wang, J. Appl. Phys. **89**, 3753 (2001).
17. C.A. Wang, H.K. Choi, D.C. Oakley, G.W. Charache, J. Cryst. Growth **195**, 346 (1998).
18. M.B. Clevenger, C.S. Murray, S.A. Ringel, R.N. Sacks, L. Qin, G.W. Charache, D.M. DePoy, 'Optical Properties of Thin Semiconductor Device Structures with Reflective Back-Surface Layers,' AIP Conf. Proc. 460, 327-334 (1999).

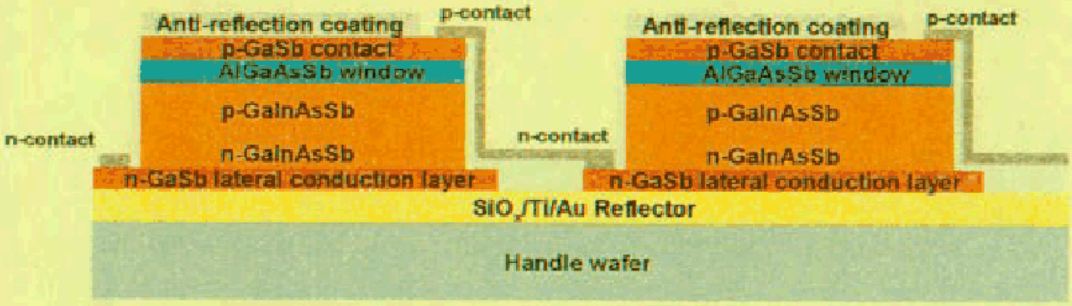

FIGURE 1. Schematic structure of wafer-bonded GaInAsSb/AlGaAsSb/GaSb series-interconnected TPV structure on GaAs handle wafer.

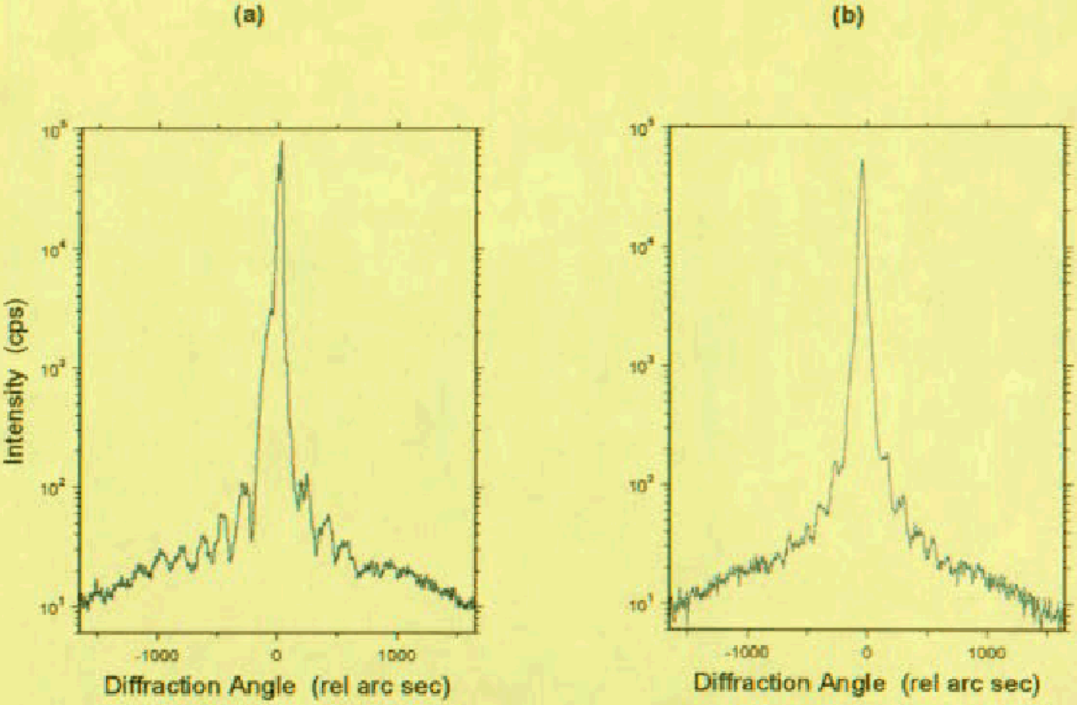

FIGURE 2. X-ray diffraction of (a) control GaInAsSb/AlGaAsSb/GaSb TPV wafer and (b) wafer-bonded GaInAsSb/AlGaAsSb/GaSb TPV structure.

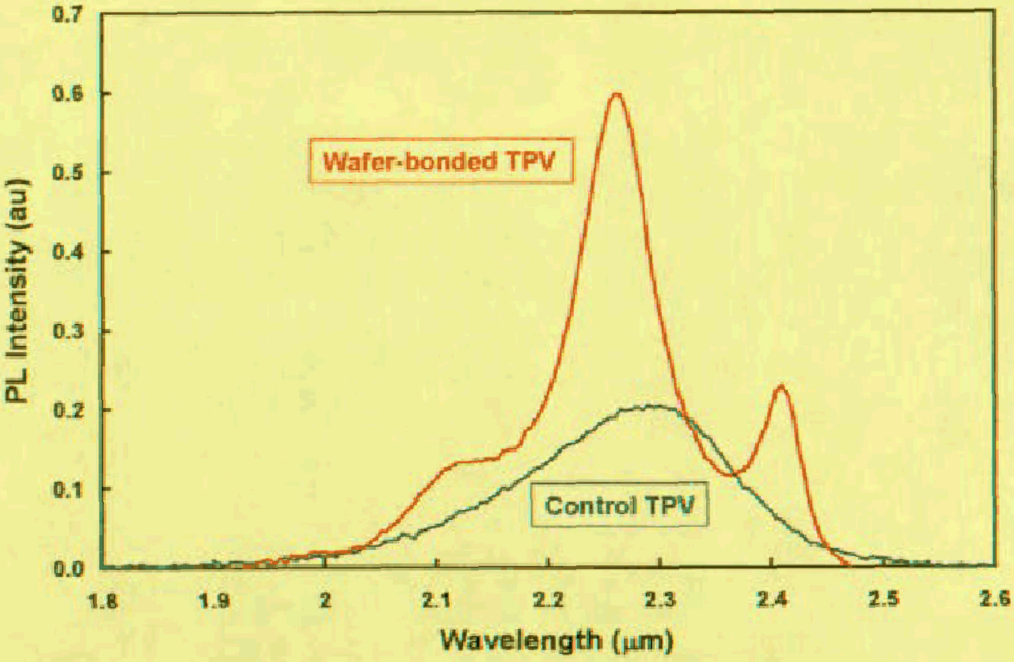

FIGURE 3. 300 K photoluminescence of control and wafer-bonded GaInAsSb/AlGaAsSb/GaSb TPV structures.

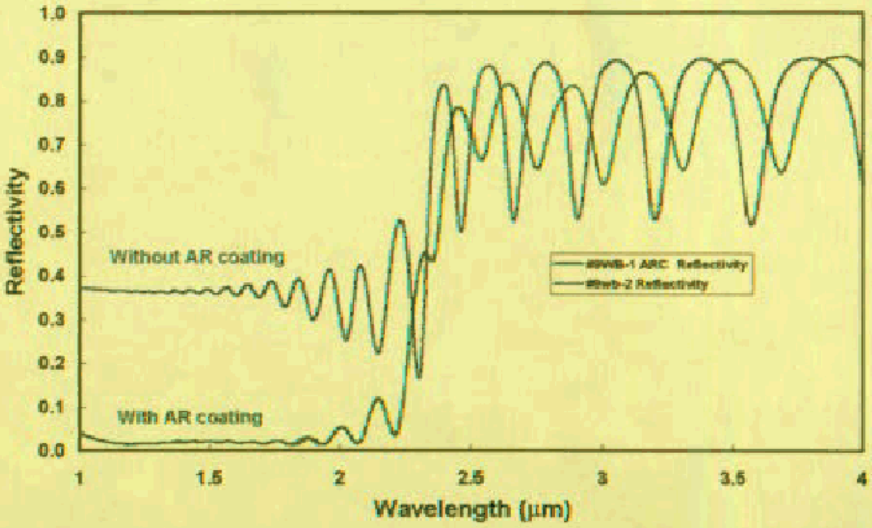

FIGURE 4. Reflectivity spectrum of uncoated and AR-coated wafer-bonded GaInAsSb/GaSb TPV structure. The TPV device structure is 4 μm thick. Thinner device layers will increase the resonant fringe spacing.

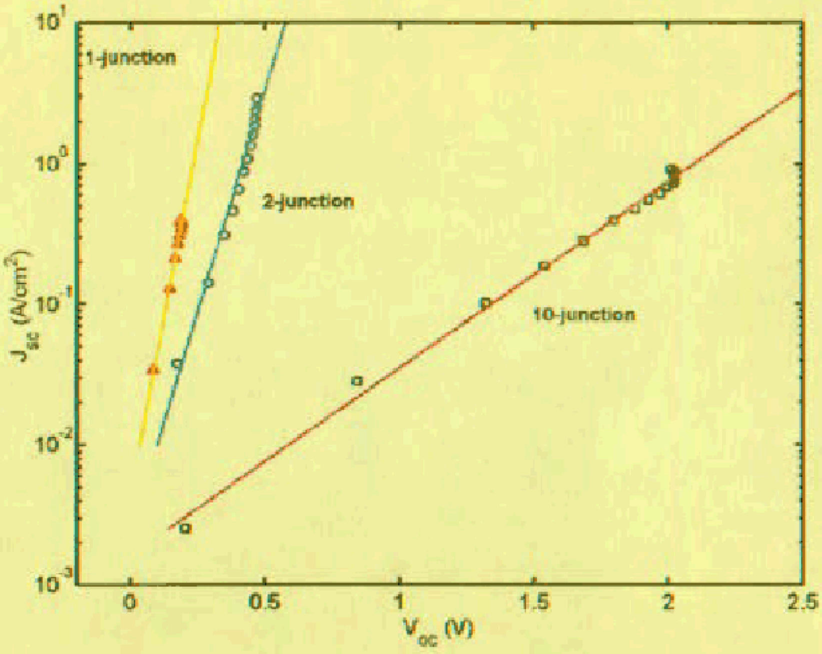

FIGURE 5. Semilogarithmic plot of J_{sc} versus V_{oc} for wafer-bonded GaInAsSb/AlGaAsSb/GaSb TPV devices.