High-Performance $In_{0.53}Ga_{0.47}As$ Thermophotovoltaic Devices Grown by Solid Source Molecular Beam Epitaxy

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***Abstract*—$In_{0.53}Ga_{0.47}As$-based monolithic interconnected modules (MIMs) of thermophotovoltaic (TPV) devices lattice-matched to InP were grown by solid source molecular beam epitaxy. The MIM device consisted of ten individual $In_{0.53}Ga_{0.47}As$ TPV cells connected in series on an InP substrate. An open-circuit voltage (V_{oc}) of 4.82 V, short-circuit current density (J_{sc}) of 1.03 A/cm^2 and fill factor of ~73% were achieved for a ten-junction MIM with a bandgap of 0.74 eV under high intensity white light illumination. Device performance uniformity was better than 1.5% across a full 2-in InP wafer. The V_{oc} and J_{sc} values are the highest yet reported for 0.74-eV band gap n-p-n MIM devices.**

***Index Terms*—InGaAs, MBE, MIM, TPV.**

I. INTRODUCTION

MONOLITHIC interconnected modules (MIMs) of thermophotovoltaic (TPV) devices based on InGaAs grown on InP substrates are being explored for a variety of terrestrial and space energy conversion applications [1]–[5]. Most TPV systems are designed for thermal sources that operate in the temperature range of 1000–2000 K. The low energy spectral irradiance peak from such black body sources necessitates photovoltaic cells having bandgaps in the range of 0.55–0.74 eV in order to achieve high TPV conversion efficiency and a reasonable power density. Due to the range of bandgaps accessible by $In_xGa_{1-x}As$ alloys, $In_xGa_{1-x}As$ photovoltaic devices with compositions between $x = 0.53$ ($E_g = 0.74$ eV) and $x = 0.75$ ($E_g = 0.55$) are receiving considerable attention for TPV applications [4]–[6]. To date, all reported $In_xGa_{1-x}As$ TPV devices have been grown by metal-organic vapor-phase epitaxy (MOVPE). However, molecular beam epitaxy is of interest as an alternative growth technique due to its extreme precision and growth uniformity, in addition to expanding the growth parameter space over which TPV materials and devices may be optimized. This letter reports the first growth and device results for solid source molecular beam epitaxy (MBE) grown $In_{0.53}Ga_{0.47}As$/InP TPV devices.

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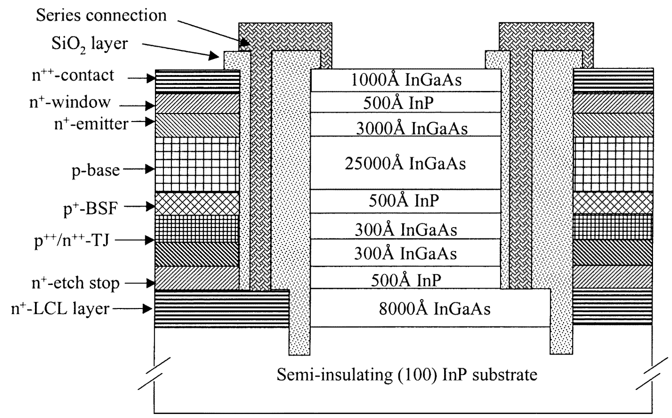

Fig. 1. Lattice-matched $In_{0.53}Ga_{0.47}As$ n-p-n thermophotovoltaic device structure.

II. MBE GROWTH AND DEVICE PROCESSING

Lattice-matched $In_{0.53}Ga_{0.47}As$ TPV devices were grown on (100) semi-insulating Fe-doped InP substrates in a solid source MBE system using valved cracker sources for both arsenic and phosphorus. The basic n-p-n structure shown in Fig. 1 uses the desired n-p cell configuration with an n-type $In_{0.53}Ga_{0.47}As$ lateral conduction layer (LCL) to interconnect strings of lateral devices in series to achieve a TPV monolithic interconnected module [4]–[6]. The substrate oxide desorption and the first stages of growth were monitored using reflection high-energy electron diffraction (RHEED). Once the oxide was fully desorbed, growth of a 0.2-μm thick undoped InP buffer layer was initiated at ~460 °C under a stabilized P_4 flux prior to growth of the TPV device structure. This process yields a strong, very streaky (2 × 4) surface reconstruction RHEED pattern. All subsequent InP layers were grown at a substrate temperature of 460 °C. The $In_{0.53}Ga_{0.47}As$ layers were grown at a substrate temperature of 525 °C, with the exception of the highly doped tunnel junction layers, which were grown at 490 °C.

Growth temperature of the substrate was monitored and controlled in real-time using an optical pyrometer with a feedback control loop to account for both emissivity variations and stray light from hot effusion cells. This precise temperature control produced TPV cells with a compositional uniformity of lattice-matched $In_{0.53}Ga_{0.47}As$ layers of better than ±0.5% across a 2-in diameter InP wafer as measured by double crystal x-ray diffraction. Because InP and InGaAs etch selectively using HCl and a mixture of $H_3PO_4 : H_2O_2 : H_2O$ (3 : 4 : 1 by volume), the exact position in the structure is known as the device is pro-

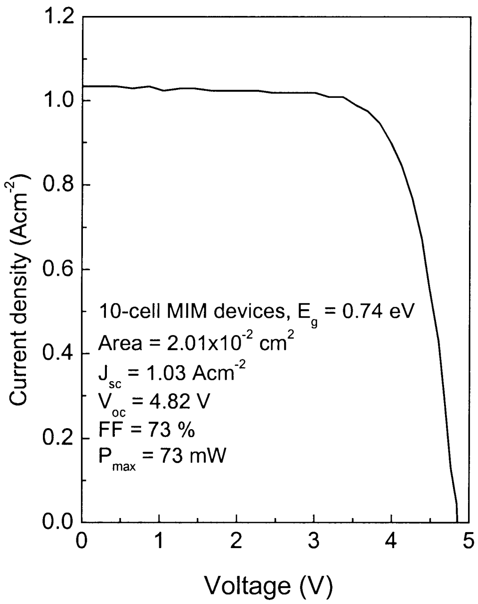

Fig. 2. Current density–voltage (J–V) characteristic of a ten-cell $In_{0.53}Ga_{0.47}As$ MIM with $E_g = 0.74$ eV.

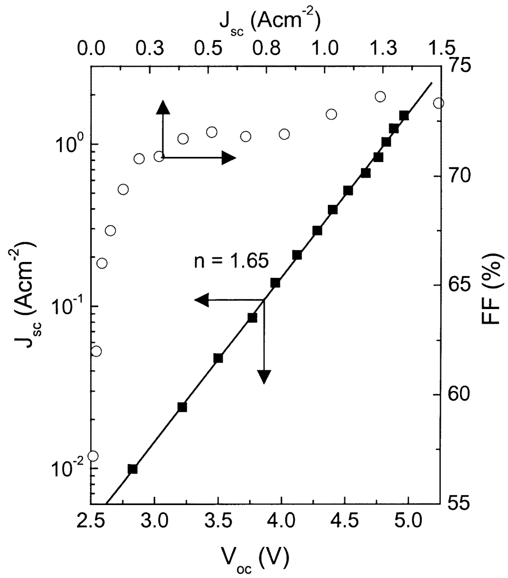

Fig. 3. Variation of short-circuit current density ($J_{\rm sc}$) with open-circuit voltage ($V_{\rm oc}$) and fill factor (FF) with J_{sc} for a ten-cell MIM with $E_g = 0.74$ eV obtained as a function of incident light intensity.

cessed. Using stylus profilometery, it was found that the depth of the back contact layer (LCL) varied by a maximum of 1% across a 2-in wafer. Conventional Ti–Au (200 Å/3 μm) metallization was used for both front and back ohmic contacts. A sputter deposited SiO_2 dielectric layer was used to prevent the interconnect metallization from short-circuiting the individual cells. No intentional antirefection coating (ARC) was deposited on the top surface and the cap layer was removed before the quantum efficiency measurements.

III. Results and Discussion

To characterize the completed TPV MIMs, current density versus voltage (J–V) measurements were performed under high intensity white light illumination. The light source is a quartz halogen tungsten lamp whose spectral emission fits a graybody spectrum with a temperature of 1920 K and emissivity of 0.0230. Fig. 2 shows the light J–V characteristics obtained from a ten-cell series interconnected MIM. Short-circuit current density ($J_{\rm sc}$) and open-circuit voltage ($V_{\rm oc}$) values of 1.03 A/cm^2 and 4.82 V were obtained, respectively, which are the highest reported to date for 0.74-eV band gap MIM n-p-n devices. Previous high values (0.84 A/cm^2 and 4.1 V) [4] were obtained for MOVPE grown p-n $In_{0.53}Ga_{0.47}As$/InP TPV cells with similar device design, fabrication process and testing methods. The variation in $V_{\rm oc}$ across a 2-in wafer was less than $\pm$1.5%, indicating excellent lateral uniformity in layer thickness, composition and material quality. Hence, SSMBE grown material can easily facilitate larger area devices (4 cm^2) better suited for assembling TPV arrays, as well as increase the yield of highly performing devices from a single wafer.

Fig. 3 shows $J_{\rm sc}$ versus $V_{\rm oc}$ results of a ten-cell MIM device as a function of illumination intensity, where an increase in $J_{\rm sc}$ values corresponds to an increase in light intensity for the J–V measurements. It can be seen from this figure that $V_{\rm oc}$ increases logarithmically with $J_{\rm sc}$, as expected from the ideal diode model. By performing a linear fit of the data in Fig. 3 and using the relation in equation (1) where k is the Boltzmann constant, and $T_{\rm Cell}$ is the temperature of the cell during measurement (298 K)

$$J_{\rm sc} = J_o \left\{ \exp\left(\frac{qV_{\rm oc}}{nkT_{\rm Cell}} \right) - 1 \right\}. \tag{1}$$

n, the diode ideality factor and J_o, the dark-current density were estimated [2], [7]. Assuming a single ideality factor, the linear fit yielded $n \approx 1.65$, indicating that current mechanisms other than diffusion ($n = 1$) are active such as depletion-region recombination. It was found that $n \approx 1.65$ even at low injection levels confirming this is not a high injection effect. The source for a possible recombination center is currently under investigation using deep level transient spectroscopy (DLTS) and reverse current density versus temperature measurements. The fill factor (FF) as a function of $J_{\rm sc}$ is also plotted in Fig. 3, which approaches 73% at higher illumination intensities. This compares favorably with previously reported values of $\sim$75% for lattice-matched p-n $In_{0.53}Ga_{0.47}As$/InP TPV cells grown using MOCVD [4].

A typical external quantum efficiency (EQE) response for an MBE-grown MIM device is shown in Fig. 4. The sharp cutoff at the long wavelength band edge and the high EQE values ($\sim$70% between 1000 nm and 1500 nm without benefit of an anti-reflection coating) indicates a high carrier lifetime and a diffusion length in excess of the 2.5-μm base thickness for minority carrier electrons in the p-type $In_{0.53}Ga_{0.47}As$ base layer. This is consistent with the low carrier recombination rate implied by the high $V_{\rm oc}$ and $J_{\rm sc}$ values.

IV. Conclusion

Lattice-matched $In_{0.53}Ga_{0.47}As$–InP TPV devices on InP substrates have been designed, grown, fabricated, and tested using MBE. An open-circuit voltage of 4.82 V and short-circuit

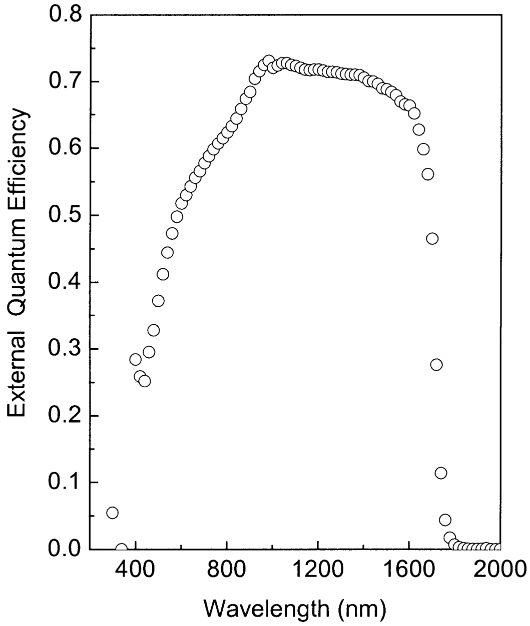

Fig. 4. External quantum efficiency results for a ten-cell $In_{0.53}Ga_{0.47}As$ MIM.

current density of 1.03 A/cm^2 were achieved for a ten-junction MIM, which are the highest values reported for TPV MIM of any material with a bandgap of 0.74 eV to date. The I–V results were corroborated by very efficient carrier collection observed using EQE measurements. Furthermore, device performance uniformity was measured to be better than $\pm 1.5\%$ across a 2-in diameter InP wafer. These results demonstrate that solid source molecular beam epitaxy has the ability to generate high-performance $In_{0.53}Ga_{0.47}As$ TPV devices and therefore has great potential for achieving high quality $In_xGa_{1-x}As$ TPV devices with lower bandgaps using appropriately engineered substrates currently under development.

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