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A Study of Contacts and Back-Surface Reflectors for 0.6eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ Thermophotovoltaic Monolithically Interconnected Modules

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A Study of Contacts and Back-Surface Reflectors for 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ Thermophotovoltaic Monolithically Interconnected Modules

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Abstract

Thermophotovoltaic (TPV) systems have recently rekindled a high level of interest for a number of applications. In order to meet the requirement of low-temperature (~1000°C) TPV systems, 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ TPV monolithically interconnected modules (MIMs) have been developed at the National Renewable energy Laboratory (NREL)[1]. The successful fabrication of $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ MIMs depends on developing and optimizing of several key processes. Some results regarding the chemical vapor deposition (CVD)-SiO_2 insulating layer, selective chemical etch via sidewall profiles, double-layer antireflection coatings, and metallization via interconnects have previously been given elsewhere [2]. In this paper, we report on the study of contacts and back-surface reflectors. In the first part of this paper, Ti/Pd/Ag and Cr/Pd/Ag contact to n-$InAs_{0.32}P_{0.68}$and p-$Ga_{0.32}In_{0.68}As$ are investigated. The transfer length method (TLM) was used for measuring of specific contact resistance R_c. The dependence of R_c on different doping levels and different pre-treatment of the two semiconductors will be reported. Also, the adhesion and the thermal stability of Ti/Pd/Ag and Cr/Pd/Ag contacts to n-$InAs_{0.32}P_{0.68}$and p-$Ga_{0.32}In_{0.68}As$ will be presented. In the second part of this paper, we discuss an optimum back-surface reflector (BSR) that has been developed for 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ TPV MIM devices. The optimum BSR consists of three layers: ~1300Å MgF_2 (or ~1300Å CVD SiO_2) dielectric layer, ~25Å Ti adhesion layer, and ~1500Å Au reflection layer. This optimum BSR has high reflectance, good adhesion, and excellent thermal stability.

Contacts

0.6-eV TPV MIMs usually operate at high current densities of more than 2 A/cm^2. A suitable contact system for these devices has to satisfy the following three requirements: low specific contact resistance (our modeling work indicated that this value should be $<1x10^{-4}$ ˜ cm ^{2}), excellent long-term thermal stability, and good adhesion. Also, low-cost and simple fabrication processing need to be considered for larger-scale use. In this study, two contact systems, including Ti/Pd/Ag and Cr/Pd/Ag, have been investigated. We show that low contact resistance and good adhesion of Ti and Cr are obtained with both n-$InAs_{0.32}P_{0.68}$ and p-$Ga_{0.32}In_{0.68}As$. Ag is used as the conduction layer because of low cost and high conductivity. In these two contact systems, the Pd film works as a Ag diffusion barrier layer.

Dependence of specific contact resistance on the doping level of n-$InAs_{0.32}P_{0.6}$

We investigated the dependence of R_c to both Ti and Cr for different doping levels of n-$InAs_{0.32}P_{0.68}$. In the 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ TPV converter structure, n-$InAs_{0.32}P_{0.68}$ and p-$Ga_{0.32}In_{0.68}As$ serve as contact layers. The n-$InAs_{0.32}P_{0.68}$ layer also serves as an emitter layer of the cell-isolated diode (CID). To minimize the absorption of the n-$InAs_{0.32}P_{0.68}$ layer and to optimize the quality of the CID, the n-$InAs_{0.32}P_{0.68}$ layer cannot be doped to high levels. Therefore, one must study the dependence of R_c on the doping level of the n-$InAs_{0.32}P_{0.68}$ layer. Figure 1 shows the dependence of R_c on different doping levels (N_e) of the n-$InAs_{0.32}P_{0.68}$ layer. As shown in Figure 1, R_c increases with decreasing N_e. But, even if N_e is reduced to $1x10^{18}$ cm^{-3}, R_c can still meet the requirement for these devices.

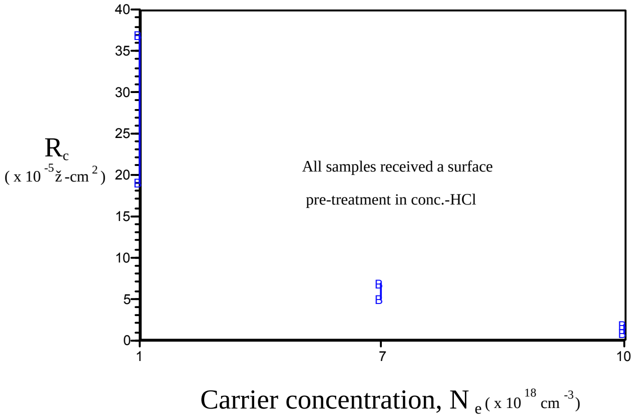


Figure 1. The dependence of R_c on the doping N_e level of n-$InAs_{0.32}P_{0.68}$.

Dependence of specific contact resistance on pre-treatment of semiconductors

The dependence of R_c on different pre-treatments of n-$InAs_{0.32}P_{0.68}$ and p-$Ga_{0.32}In_{0.68}As$ was investigated. We found that removing the native oxide from the surface of semiconductors can improve adhesion and reduce specific contact resistance. Figure 2 shows that the n-$InAs_{0.32}P_{0.68}$ sample received a dip in concentrated HCl before metallization has the lowest R_c. The results for p-$Ga_{0.32}In_{0.68}As$ are similar.

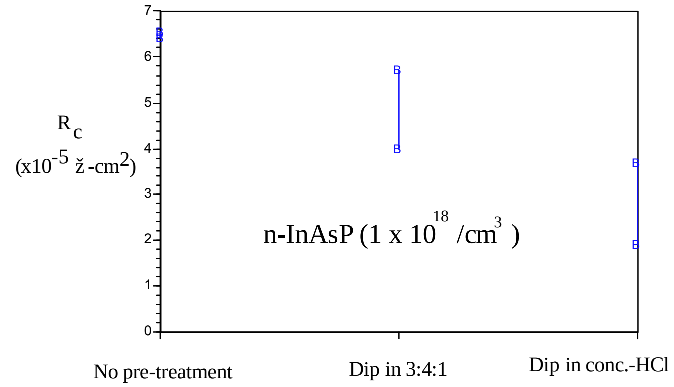


Figure 2. The dependence of R_c on different pre-treatments of n-$InAs_{0.32}P_{0.68}$.

Specific contact resistance

Figure 3 illustrates the specific contact resistance of Ti/Pd/Ag and Cr/Pd/Ag contacts to n-InAs$_{0.32}$P$_{0.68}$ and p-Ga$_{0.32}$In$_{0.68}$As. The carrier concentration of n-InAs$_{0.32}$P$_{0.68}$ and p- Ga$_{0.32}$In$_{0.68}$As are 1x10^{18} cm^{-3} and 1x10^{19} cm^{-3}, respectively. It can be seen that all of these results can meet the requirements for the MIM design. R_c of the Cr contact system is slightly higher than that of the Ti contact system.

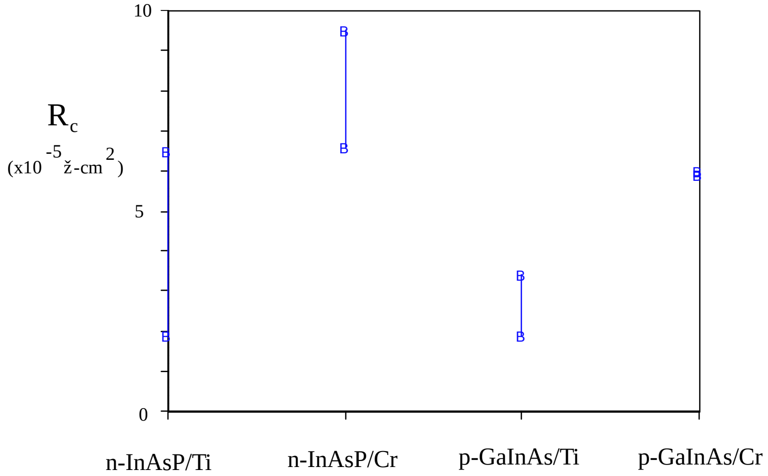


Figure 3. The specific contact resistance of Ti/Pd/Ag and Cr/Pd/Ag contacts to n-InAs$_{0.32}$P$_{0.68}$ and p-Ga$_{0.32}$In$_{0.68}$As.

Adhesion

All samples with Ti/Pd/Ag and Cr/Pd/Ag contacts to n-InAs$_{0.32}$P$_{0.68}$ and p-Ga$_{0.32}$In$_{0.68}$As have passed a Scotch tape test. Cr/Pd/Ag fine contact grids have better adhesion to p-Ga$_{0.32}$In$_{0.68}$As than Ti/Pd/Ag fine grids.

Thermal stability

Finally, the thermal stability of Ti/Pd/Ag contacts to n-InAs$_{0.32}$P$_{0.68}$ and p-Ga$_{0.32}$In$_{0.68}$As has been inspected. Two samples, one of Ti/Pd/Ag contacts to n-InAs$_{0.32}$P$_{0.68}$ (1x10^{18} cm^{-3}) and another of Ti/Pd/Ag contacts to p-Ga$_{0.32}$In$_{0.68}$As (1x10^{19} cm^{-3}), have been exposed to 80°C for 120 hours. Figure 4 shows the changes of specific contact resistance for these two samples before and after thermal stress. It can be seen that R_c is slightly improved for both samples after the thermal treatment.

In summary, experimental results, including specific contact resistance, adhesion, and thermal stability, demonstrate that Ti/Pd/Ag or Cr/Pd/Ag contacts to n-InAs$_{0.32}$P$_{0.68}$ and p-Ga$_{0.32}$In$_{0.68}$As can meet the requirements of the TPV MIM. These two contact systems have already been integrated into NREL's 0.6-eV Ga$_{0.32}$In$_{0.68}$As/InAs$_{0.32}$P$_{0.68}$ TPV MIMs. We have fabricated a 4-cell 0.25 cm^2, 0.6-eV Ga$_{0.32}$In$_{0.68}$As/InAs$_{0.32}$P$_{0.68}$ TPV MIM with a fill factor of 71%.

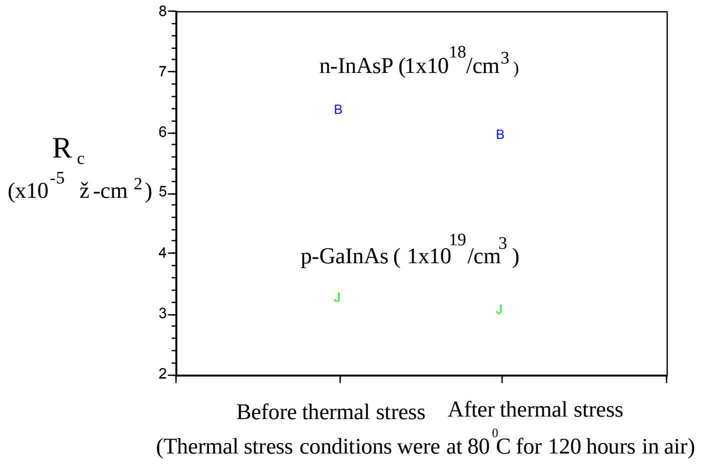


Figure 4. The thermal stability of Ti/Pd/Ag contacts to n-$InAs_{0.32}P_{0.68}$ and p-$Ga_{0.32}In_{0.68}As$.

Back-surface reflector

The TPV system requires a spectral control component to recoup low-energy photons, which is crucial to the efficiency of the system. Two techniques have been used for realizing the spectra control in TPV systems: selective filters serve as the front-surface spectral control and back-surface reflectors (BSRs) serve as back-surface spectral control. Compared to the selective filters, the back-surface reflector has much less parasitic absorption of the above-bandgap radiation, a wider bandwidth, and a lower reflection of above-bandgap photons. In general, there are a number of criteria that must be simultaneously satisfied for a BSR to succeed. These criteria include high reflectance, low contact resistance, strong adhesion, and thermal stability. Because the BSR can be directly prepared on a semi-insulating substrate, the contact resistance is not an issue in the TPV MIMs. NREL's MIMs use a novel, interdigitated contacting scheme. This new design offers an attractive solution to a number of problems confronting TPV device performance, including problems with the BSR. Our interdigitation design allows us to realize the full performance potential of a well-designed BSR by minimizing parasitic free-carrier absorption. In this section, we summarize the experimental results and present the optimum BSR structure for 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ TPV MIMs.

We use a BSR structure with three layers, which includes a dielectric layer, an adhesion layer, and a reflection layer. In general, the metals with best infrared (IR) reflectance are the noble metals. We selected a Au film with a thickness of 1500Å as the reflection layer. In a BSR structure, the dielectric layer serves not only as a diffusion barrier, but also, as an optical mismatch between the metal and semiconductor for improving the reflectance in the IR wavelength range. Both SiO_2 and MgF_2 films have been used as the dielectric layer in our BSR structure. They both have excellent insulating properties and lower refractive index. SiO_2 films were prepared by the CVD technique at about 350°C. MgF_2 films were deposited by the thermal evaporation technique at room temperature. Our experimental results indicate that the reflectance of the BSR with a MgF_2 dielectric layer is slightly higher than that with a SiO_2 layer. This is reasonable because the refractive index of MgF_2 (n=1.38) is slightly lower than that of the SiO_2 film (n=1.46). In addition, there is an absorption peak at about 7 μm for the BSR with a SiO_2 dielectric layer from Fourier transform infrared (FTIR) measurement. Conversely, the BSR with a MgF_2 layer does not have this absorption peak (see Figure 5). Based on these results, we prefer to use MgF_2 film as a dielectric layer in our TPV devices.

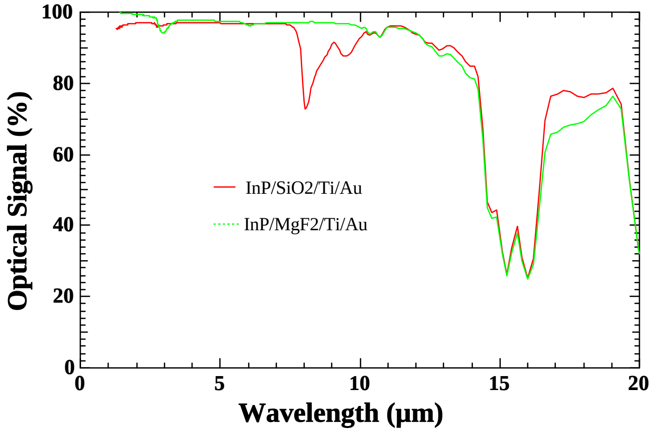


Figure 5. Comparison of the reflectance between two BSRs with a SiO_2 and MgF_2 dielectric layer in the IR-wavelength range.

Figure 6 shows a comparison of the reflectance of four BSRs with different thicknesses of the SiO_2 dielectric layer. As shown in this figure, the BSR with a SiO_2 dielectric layer having a thickness of ~1300Å has the highest reflectance. The thin Ti film serves as an adhesion layer in our BSR structure. The improvement of the BSR's adhesion always results in reducing reflectance; therefore, it is necessary to optimize the Ti thickness. We found that the BSR with a 25Å Ti film has the highest reflectance and excellent adhesion.

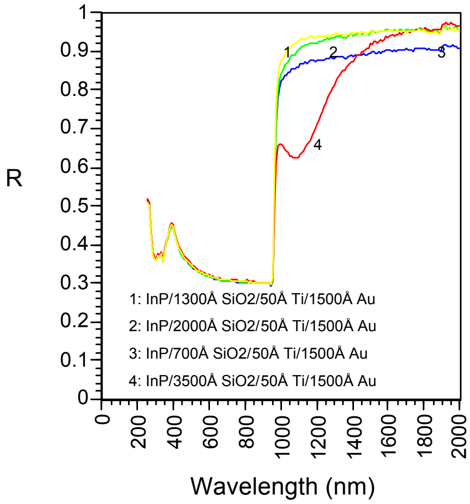
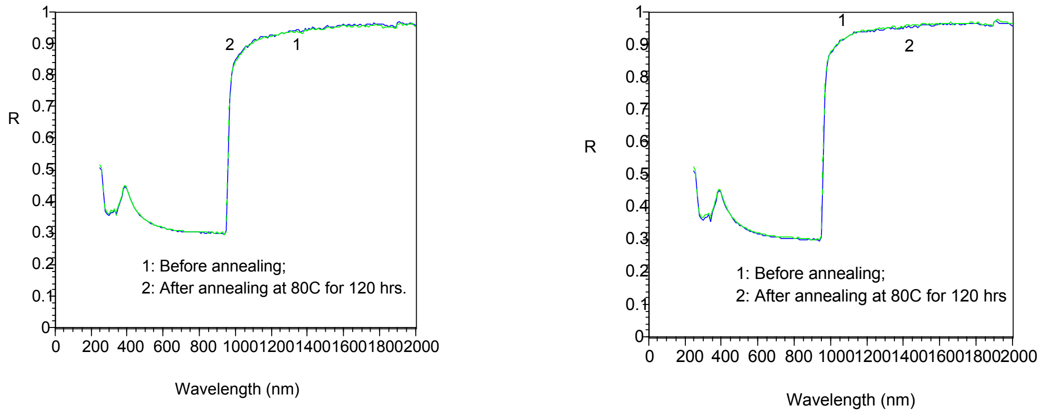


Figure 6. Comparison of the reflectance of four BSRs with different thicknesses of the SiO_2 dielectric layer.

We also studied the thermal stability of the BSRs. Two BSR samples, which included SiO_2 and MgF_2 dielectric layers individually, were prepared for this study. Both

BSRs received a thermal annealing treatment at 80°C in air for 120 hours. Two techniques, reflectance measurement and secondary-ion mass spectroscopy (SIMS) analysis, have been used to inspect the change of the two BSR samples. Figures 7a and 7b show the change of the reflectance before and after the thermal treatment for two BSRs with SiO_2 and MgF_2 dielectric layers, respectively. As shown in these two figures, there is no change of the reflectance after the thermal treatment. SIMS results also indicate that the Au profile does not change after the thermal treatment. Therefore, the optical measurement and SIMS analysis demonstrate that our BSRs have excellent thermal stability.



7a

7b

Figure 7. The change of the reflectance after the thermal treatment for two BSRs with a SiO_2 (7a) and a MgF_2 (7b) dielectric layer, respectively.

As a result of this investigation of BSRs, the optimum BSR should consist of a ~1300Å MgF_2 (or SiO_2) dielectric layer, ~25Å Ti adhesion layer, and ~1500Å Au reflection layer. The optimum BSR structure has been used on two samples: one is a semi-insulated (SI) InP wafer, and the other is a 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ device on a SI-InP substrate without contact grids and antireflection coating layer. As shown in Figure 8, an optimum BSR on a semi-insulated InP substrate has a very high reflectance of more than 90% in the wavelength range between 2–12 µm. It can also be seen from Figure 9 that the reflectance of an optimum BSR on a 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ device is in the range of 80%-92%. The somewhat lower reflectance is due to the free-carrier absorption of the doped layers of the device.

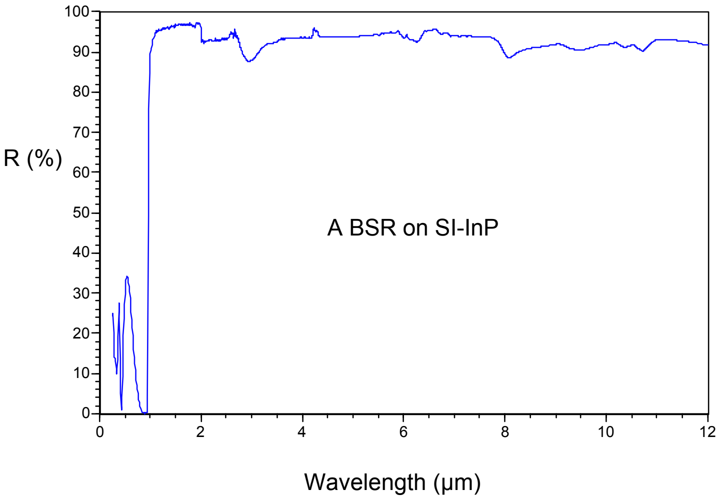


Figure 8. The reflectance of an optimum BSR on a SI-InP substrate with a double antireflection (AR) layer.

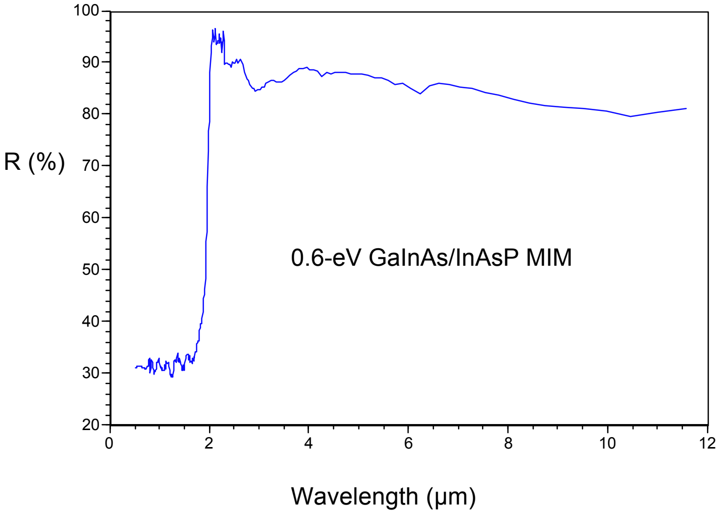


Figure 9. The reflectance of an optimum BSR on a 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ device without metal contact grids and AR coating layer.

In summary, an optimum back-surface reflector has been developed for NREL's 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ TPV MIMs. The optimum BSR consists of three layers: a ~1300Å MgF_2 (or ~1300Å CVD SiO_2) dielectric layer, a ~25Å Ti adhesion layer, and a ~1500Å Au reflection layer. This optimum BSR has high reflectance, strong adhesion, and excellent thermal stability. A reflectance of 80%-92% in the wavelength range between 2–12 μm has been achieved for a BSR on a 0.6-eV $Ga_{0.32}In_{0.68}As/InAs_{0.32}P_{0.68}$ device.

Acknowledgment

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[2] J.S. Ward et al., "A Novel Design for Monolithically Interconnected Modules (MIMs) for Thermophotovoltaic Power Conversion," Proc. Third NREL Conf. on TPV Gen. of Elect., 1997, AIP 401, pp.227.