# THERMOPHOTOVOLTAIC PROPERTIES OF $Bi_2Te_3$ AND $Bi_2Se_3$

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p-tip $Bi_2Te_3$ və n-tip $Bi_2Se_3$ monokristallarının termofotovoltaik xassələri tədqiq olunmuşdur. Vahid texnoloji tsikldə diskret termik tozlanma metodu ilə alınan p-n keçidli p-$Bi_2Te_3$–n-$Bi_2Se_3$ strukturlu təbəqələr termofotovoltaik qurğularda istifadə olunmuşdur. Göstərilmişdir ki, $A^VB^{VI}$ əsaslı termofotovoltaik qurğular silisium günəş elementləri ilə müqayisədə geniş spektral həssaslığa və konsentrə olunmuş günəş şüalanmasında daha çox stabilliyə malikdir. Qurğunun xarakteristikasının yaxşılaşdırılması üçün texnologiyanın tənzimlənməsi məqsədi ilə konsentratorlu günəş elementlərinin modelləşməsi aparılmışdır

Были исследованы термофотовольтаические свойства монокристаллов $Bi_2Te_3$ p-type и $Bi_2Se_3$ . P-n пленочные структуры p-$Bi_2Te_3$–n-$Bi_2Se_3$, полученные методом дискретного термического напыления в едином рабочем цикле, были использованы в термофотовольтаических устройствах. Было показано, что термофотовольтаические устройства на основе $A^VB^{VI}$ имеют преимущества по сравнению с кремниевыми солнечными элементами в широком спектре чувствительности и стабильности концентрированного солнечного излучения. Было проведено моделирование солнечных элементов с концентратором с целью коррекции технологии для улучшения характеристик устройств.

Thermophotovoltaic properties monocrystals $Bi_2Te_3$ p-type and $Bi_2Se_3$ are investigated. P-n film structures of p-$Bi_2Te_3$–n-$Bi_2Se_3$, received by a method of discrete thermal evaporation in a uniform work cycle, are suitable for usage in thermophotovoltaic devices. It is demonstrated, that the wide spectrum of sensitivity and stability to the concentrated solar radiation of thermophotovoltaic elements on the basis of $A^VB^{VI}$ are advantage in comparison with traditional solar cells. The modelling of concentrator solar cells with thermophotovoltaic converters is carried out in order to guide the technology to increase the performance of these devices. .

## 1. INTRODUCTION

The current designs for semiconductor solar cells used for high-flux concentrator systems can be traced to developments of high thermophotovoltaic cells. These cells were operated under continuous illumination of greater than 27 W/cm$^2$. The interdigitated back contact cell, developed for the high flux conditions of thermophotovoltaic systems, was directly applied to silicon high concentration terrestrial applications. Silicon cells were operated under continuous conditions at flux densities of greater than 30 W/cm$^2$ with efficiencies of 18%. One and two dimension computer models developed to design interdigitated back contact cell were the first solar cell numerical models to provide contact-to-contact models of carrier current flows [1].

The efforts to build thermophotovoltaic systems included the development of photovoltaic cells with band gaps that matched the radiation sources and that were capable of operating at flux densities of tens of W/cm$^{-2}$. It was the requirement that the cells be capable of operation at high flux densities that made the thermophotovoltaic cell designs of interest when concentrated terrestrial solar electric generation became of serious interest in the mid 1970’s.

It was recognized quite early on that Ge cells with both contacts on the non-illuminated side would have advantages over conventional photovoltaic cell designs [2]. These advantages were to be found in the removal of the shadowing by the grid fingers and in the removal of constraints on the size of the fingers so the series resistance of the contacts could be made negligibly small. Because the diffusion technology for Ge was not well developed at the time the junction regions were formed using low temperature alloying techniques. Very lifetime intrinsic Ge wafers were obtained from ingots of lithium drifted Ge that had been originally grown for use in nuclear detectors. In addition to band gap considerations, Ge was chosen over Si because at that time the Ge minority carrier lifetime was much longer than that of Si. The interdigitated back contact cell requires a long lifetime bulk region since many of the carriers must traverse the entire thickness of the cell.

## 2. EXPERIMENTS

Offered the inherent two-dimensional nature of the concentrated solar cell did not allow the use of a conventional one dimensional analysis and a two dimensional design procedure needed to be used [1]. By taking advantage of periodicity (strip) of the structure, an analytic solution to the continuity equations could be obtained for the bulk region with the boundary conditions set by the conventional “law of the junction” at the junction boundaries to the bulk region. For our structures we had been used a procedure of simulation analysis and the equations featured in [2]. These results were used to design the cells.

Monocrystals of $Bi_2Te_3$ have been obtained by synthesis of initial components during 48 hours in quartz ampoules. Then ampoules were cooled in a temperature gradient. Samples were p-type conductivity, with concentration of carrier’s 1,1x10$^{19}$ cm$^{-3}$. $Bi_2Se_3$ have been obtained by a method of discrete thermal evaporation on substrates of latest *chopped off* monocrystal of $Bi_2Se_3$ in a (0001) plane. A film were n-type conductivity with concentration of carrier’s 1,1x10$^{19}$ cm$^{-3}$ [3].

The p-n heterojunctions have been obtained by a method high-temperature annealing samples of Si. The p-n heterojunctions are thus smooth. The factor of straightening at 0,15V is 30-40. Management of properties film is direct during their condensation enables to form in a uniform work cycle the p-n heterotransition with the set concentration of charge carriers. A film with the best parameters have been obtained at evaporation on a substrate with temperature 250-280°C, with the subsequent annealing during 20-30 minutes. The optimum speed evaporation is 2-5 nm/sec and its further increase results in deterioration of structure the films. Film p-n structures of p -$Bi_2Te_3$ – n -$Bi_2Se_3$, received by a method of discrete thermal evaporation in a uniform work cycle, are suitable for use in low-voltage straightening devices.

As a result of the perceived energy crisis, interest in terrestrial solar electric generation increased. For a number of reason's it was argued that high concentration wouldn't work [1]. Among the reasons given was that at high currents the series resistance would lower efficiency; the cells would operate at higher temperatures and therefore at lower efficiencies; it would be difficult to get rid of the heat and the grid lines would melt.

However, the thermophotovoltaic cells designs were quickly adapted to high concentration solar applications. Our efforts began to adopt the Ge thermophotovoltaic interdigitated back contact cell designs to Si high concentration interdigitated back contact cells (Fig. 1).

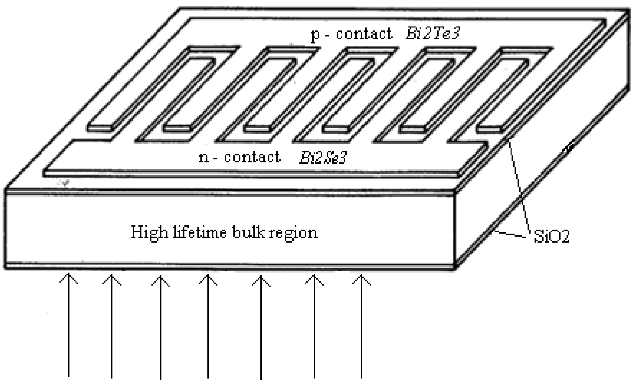


*Fig. 1.* Silicon interdigitated back contact cell with p- $Bi_2Te_3$ - п- $Bi_2Se_3$

Dimensional modelling effort were that heavy doping effects were important in the design of these cells and they needed to be incorporated into the model, if the open circuit voltage was to be properly modelled [4]. The high injection conditions encountered in concentrator cells required knowledge of both the minority carrier and majority carrier mobilities. The well established values for majority carrier mobilities, intrinsic carrier concentrations in Si weren't as well known. The doping profiles created quasi-electric fields that could influence the spectral response of the cells. Eventually the result was a model that could be used predicatively for conventional design Si cells.

The predictive nature of the model was shown at this time. A request was made to run the model for a cell that was the same as at the tope except for an $n^+pp^+$ cell. The results of this are shown in fig. 2.

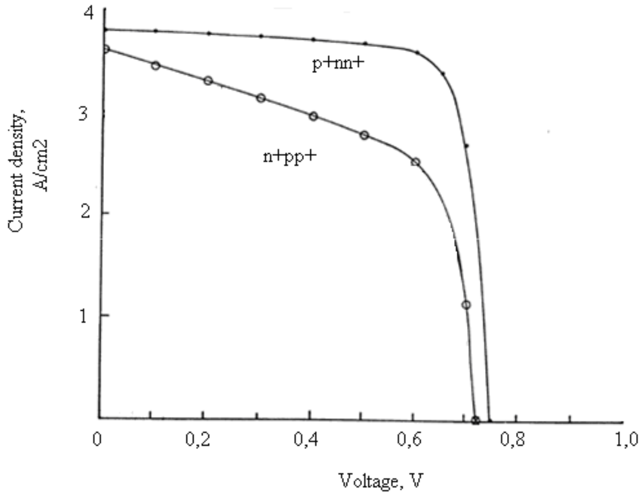


*Fig. 2.* A comparison of $p^+nn^+$ cells and $n^+pp^+$ cell performance; points – experiment.

The significant drop in performance for the $n^+pp^+$ had been observed in a number of laboratories and had been attributed to process problems [5]. However, the model correctly showed that the decrease was due to a loss of conductivity modulation in the base of the cell. The model also showed that the solution to the problem lay in the proper choice base doping density. It turns out that the understanding of high intensity conventional cells also benefits from the results of two-dimensional modelling .

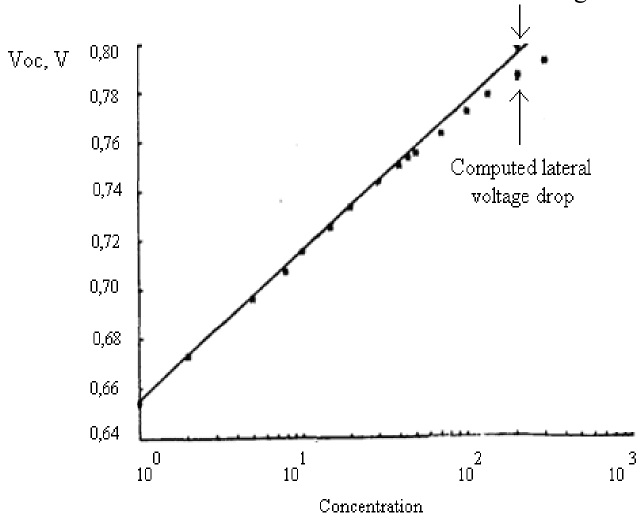


*Fig.3.* The effect on Voc of circulating currents occurring in the vicinity of a finger contact on the front surface of a cell; points – experiment.

The finger contacts of a conventional cell shade the material under the finger. At low intensities this as little effect on the device performance, but at high concentrations (suns) it can lead to a reduction in open circuit voltage as shown in fig.3. Because the voltage generated in the illuminated region is large than that of the region under the finger a circulating current is generated in the vicinity of the finger. Figure 3 shows the effect of this circulating current on

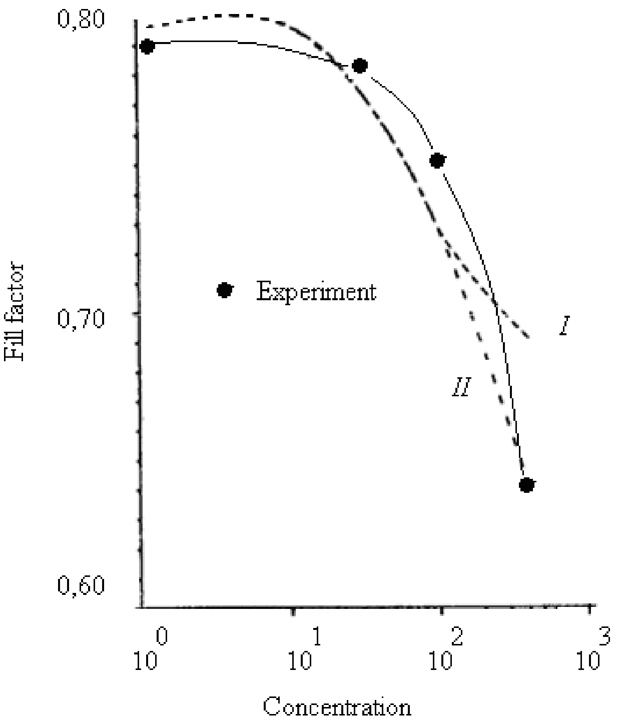


*Fig.4.* 1-dimensional (I) and 2-dimensional (II )models compared to experimentally determined fill factors of a conventional cell operated at high intensities

the open circuit voltage as a function of the illumination intensity. The effect becomes significant in the vicinity of 100 suns. This leads to the interesting observation that the cell experiences a voltage drop even under open circuit conditions.

A comparison of the results of calculating the fill factor for a conventional cell at 100 suns with a 1-dimensional and a 2-dimensional model is shown in fig. 4. The cell that is usually thought of as being one dimensional in its behaviour requires a two dimensional analysis at high intensities. In this case the 1-dimensional analysis over estimates the fill factor of the cell at high intensities. A comparison of the 1-D and 2-d models also shows that the 1-D model underestimates the effects of surface recombination as the voltage approaches open circuit voltage.

## 3. CONCLUSIONS

The problems of a solar energy conversion to electrical power by means of thermophotovoltaic systems on base $A^VB^{VI}$ are considered for high concentration solar applications. As p-n-junctions it is offered to use monocrystals $Bi_2Te_3$ p-type and $Bi_2Se_3$ n-type conduction. P-n film structures of p-$Bi_2Te_3$–n-$Bi_2Se_3$, received by a method of discrete thermal evaporation in a uniform work cycle, are suitable for usage in thermophotovoltaic devices. It is demonstrated, that the wide spectrum of sensitivity and stability to the concentrated solar radiation of thermophotovoltaic elements on the basis of $A^VB^{VI}$ are advantage in comparison with traditional solar cells. The accurate modelling of concentrator solar cells with thermophotovoltaic converters is absolutely necessary in order to guide the technology to increase the performance of these devices.

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