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Intlp compounds for Underwater Solar Energy Harvesting

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ABSTRACT

With the rising interest in oceanic monitoring, climate awareness and surveillance, the scientific community need for developing autonomous, self-sustaining Unmanned Underwater Vehicles (UUVs) increased as well. Limitations on the size, maneuverability, power consumption, and available on-site maintenance of these UUVs make a number of proposed technologies to power them harder to implement than others; solar energy harvesting stands as one of the more promising candidates to address the need for a long-term energy supply for UUVs due to its relatively small size and ease of deployment. Studies show research groups focusing on the use of Si cells (amorphous and crystalline), InGaP, and more recently Organic Photovoltaics to convert the attenuated solar spectrum under shallow depths (no deeper than 9.1 m) into electrical energy used or stored by the UUV's power management system (P. P. Jenkins et al. 2014; Walters et al. 2015). In our study, we consider the ternary compound $In_{1-x}Tl_xP$ that allows for varying the quantum efficiency of the cell, and by extension the overall harvesting efficiency of the system by altering the Tl content (x) in the compound. $In_{1-x}Tl_xP$ on InP is a low strain system since the compound exhibits very little change in its lattice constant with changing Tl content due to the comparable atomic size and forces of In and Tl allowing for relatively easy growth on InP substrates. The study focuses on studying the spectral response and comparing the performance of an optimized single junction $In_{1-x}Tl_xP$ cells to $In_{1-y}Ga_yP$ cells while accounting for the optical losses of the solar irradiance underwater for various depths.

Introduction

Water submersion of photovoltaics was first explored in the late 1970s when the US Navy expressed its interest in investigating the performance of underwater photovoltaic cells. Under the supervision and execution of Stachiw, the study was inconclusive due to uncertainties in the form of water turbidity, salinity and marine life in the locales he chose [1]. A little over 20 years after that, research in underwater photovoltaic cells rekindled after Rosa Clot et al., cited possible efficiency improvements to amorphous silicon cells under water due in large to improved thermal drift from the cells and the absence of dust collection on the surface of the panels [2-6]. Due to silicon's low absorption coefficient, Clot restricted their studies to depths not exceeding 30 cm below the water level.

In addition to going deeper underwater, this paper also studies the feasibility of using a ternary Tl-based compound to substitute amorphous silicon or more recently, InGaP cells to harvest solar energy underwater [7].

Parameters

$In_{(1-x)}Tl_xP$ was first proposed by van Schilfgaarde et al. as an infrared photodetector due to its theorized semimetal properties, allowing for its bandgap to vary as a function of the concentration of Tl incorporated [8]. The change in bandgap came with a relatively small change in the lattice parameter of the compound allowing for monolithic growth of $In_{(1-x)}Tl_xP$ compounds with very little lattice mismatch. In our work, we further expand on their calculations to extract the electronic properties of $In_{(1-x)}Tl_xP$ for submerged solar energy harvesting.

Using the commercial package WIEN2k developed by Blaha et. al., we calculate the electronic properties of the semiconductor $In_{(1-x)}Tl_xP$ varying x-content [9]. WIEN2k uses the Density Functional Theory (DFT) to calculate the electronic structure of materials, where the exchange-correlation potential can be approximated using Linear Density Approximation (LDA) or the Generalized Gradient Approximation (GGA). To avoid the overbinding that could result from using LDA, we employ the Wu-Cohen GGA method for the ab-initio calculations in our work [10], [11].

By gradually increasing the Tl content in $In_{(1-x)}Tl_xP$, we note the band structure, the corresponding optical bandgap and the lattice constant of the semi-conductor. By rearranging the Planck-Einstein relation, shown below, we can find the corresponding wavelength of the minimum energy of a photon required to promote electrons across the bandgap and accordingly choose the most appropriate Tl concentration in the ternary compound suited for our application. Figure 1 shows the change of bandgap and lattice constant as a function of increasing Tl content in $In_{(1-x)}Tl_xP$.

$$\lambda = {hc}/{E_g}$$

Where:

λ : maximum wavelength of the required incident photon in nm ,

h : Planck's constant evaluated as $4.13566751\times10^{-15}\ eV \bullet s$,

c : Speed of light $2.99792\text{x}10^{17}\ nm/s$, and

E_g : Optical bandgap of the material in eV

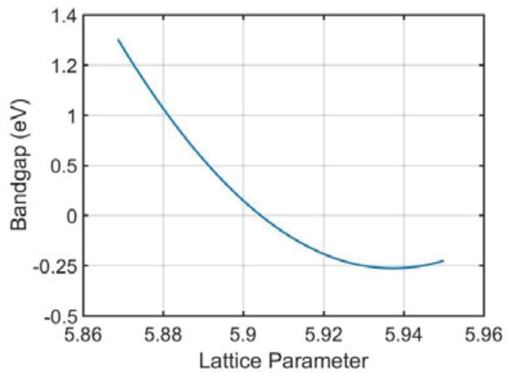

Figure 1: Optical bandgap of $In_{(1-x)}Tl_xP$ and lattice parameter as a function of increasing Tl content.

Using the provided information, we then proceed to calculate the required electronic properties of $In_{(1-x)}Tl_xP$ to simulate its performance under water following the process we have outlined previously [12][13]. For being able to harness most of the incident solar radiation at shallow depths, $In_{0.77}Tl_{0.23}P$ was used in our subsequent simulations with the following compound properties shown in Table 1.

Table 1: InTlP electronic properties calculated for our device simulations

Material	Electronic Bandgap	Effective Electron Mass	Electron Mobility	Lattice Parameter
InTlP	1.36 eV	$0.08m_0$	5700 cm^2/Vs	5.8687 Å
$In_{0.77}Tl_{0.23}P$	1.00 eV	$0.018m_0$	cm^2/Vs	5.8813 Å
TlP	-0.27 eV	$0.007m_0$	3548.7 cm^2/Vs	5.96 Å

Device simulations

Using the commercial package, Sentaurus TCAD, we were able to measure the performance of an $In_{0.77}Tl_{0.23}P$ cell operating under water, built as a single junction cell illuminated by a standard AM1.5G spectrum while varying the depth of water. To further bolster the robustness of the model, water's optical properties were incorporated into the software to account for the attenuation of light with increasing depth. It should be of note however, that this only becomes a discernable factor in the overall cell efficiency at depths exceeding 25 cms. This is because of water's strong dispersion of light wavelengths over 700 nm. It also helps justify picking InTlP over silicon for underwater applications despite its lower spectral range [7], [14].

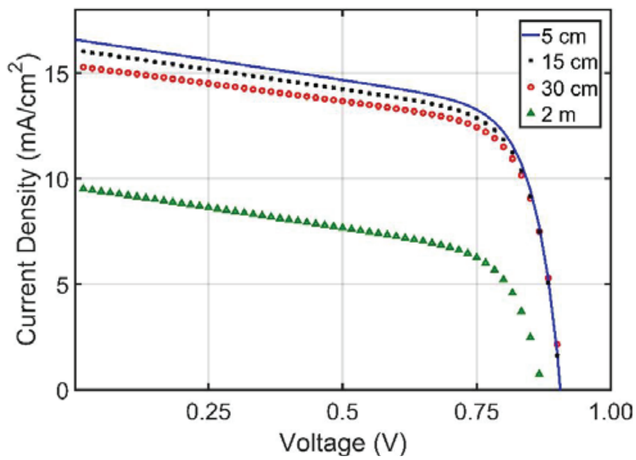

Figure 2: J-V curves of $In_{0.77}Tl_{0.23}P$ under various depths of water. For shallow depths, the deterioration in power is almost linear but exhibits a near logarithmic drop in power output as the depth increases beyond a few centimeters. The curve marked 2m shows the J-V curve of the same InTlP cell dropping by a little less than 10% when compared to when it is only 5 cm underwater.

Figure 2 compares the J-V curve for $In_{0.77}Tl_{0.23}P$ at various depths, illustrating how the performance drops at increasing depths. It should be noted that despite the efficiency falling below 10% for depths exceeding 2 meters, the efficiency is measured relative to the AM1.5G spectrum, the higher wavelengths of which are attenuated by water, thus leading to a lower rating than if wavelengths above 700 nm were not considered as part of the input to the cell. Table 2 summarizes the overall efficiency of the $In_{0.77}Tl_{0.23}P$ for increasing depths of water.

Table 2: Performance parameters of $In_{77}Tl_{23}P$ under water.

Depth	**Rated Efficiency**	Relative Efficiency	**J_{sc} mA/cm^2**	V_{oc} V	**Power Converted W/m^2**
0	14.42%	14.42 %	18.296	0.82	14.42
5 cm	12.99*%	14.14 %	16.476	0.82	12.99
15 cm	12.68%	14.05 %	16.082	0.82	12.68
30 cm	11.87%	13.81 %	15.063	0.82	11.87
200 cm (2 m)	7.10%	28.62 %	9.752	0.78	7.1
500 cm (5 m)	3.29%	31.07 %	5.44	0.75	3.29

Comparing our cell's performance to the InGaP cell proposed by Jenkins et al. shows a relative improvement of approximately 31.6% when the cells are submerged under 5 meters of water, with absolute power ratings being approximately 3.29 mW/cm^2 and 2.5 mW/cm^2 for $In_{0.77}Tl_{0.23}P$ and InGaP respectively [7]. Additionally, our cell benefits from the low lattice mismatch it has with InP allowing for epitaxial growth on an InP substrate with minimal complications.

Conclusions

This analysis enclosed herewith shows that InTlP can be considered as a contending candidate for solar energy harvesting in submerged environments with moderate success, offering advantages in growth due to its low lattice mismatch with InP, versatility as a result of the compound being tunable with Tl concentration and improved power performance under water depths potentially exceeding 5 meters.

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