Investigation of a temperature tolerant InGaP (GaInP) converter layer for a $^{63}$Ni betavoltaic cell

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Abstract

A prototype InGaP $p^+–i–n^+$ mesa photodiode was studied for its potential as the energy conversion device in a $^{63}$Ni betavoltaic cell; its electrical performance was analysed across the temperature range $−20$ °C to $100$ °C. The results show that the InGaP detector when illuminated with a laboratory $^{63}$Ni radioisotope beta particle source had a maximum output power of 0.92 pW at $−20$ °C, this value decreased at higher temperatures. A decrease in the open circuit voltage and in the cell internal conversion efficiency were also observed when the temperature was increased: at $−20$ °C, the open circuit voltage and the cell internal conversion efficiency had values of 0.69 V and 4%, respectively. A short circuit current of 4.5 pA was measured at $−20$ °C.

Keywords: InGaP, betavoltaic, semiconductors

(Some figures may appear in colour only in the online journal)
140 °C, whilst Tritium betavoltaic InGaP cells were characterised by Cabauy et al [15, 16] at room temperature. AlInP has been also successfully used in x-ray photovoltaic microbattery [17]; whilst an InGaP alphaparticle device has been reported by Cress et al [18]. However, it should be noted that the use of an alpha particle source, with respect to beta or x-ray sources, increases the converter device damage risk, since higher energetic particles impinge on the device. The use of InGaP (direct bandgap of ~1.9 eV for In0.5Ga0.5P at room temperature [19–21]) as converter devices in betavoltaic microbatteries is attractive: firstly, In0.5Ga0.5P has higher linear attenuation coefficients than AlInP and other with bandgap materials, this results in a higher quantum efficiency per unit thickness compared to those of wide bandgap materials such as GaAs, SiC and AlInP; secondly, In0.5Ga0.5P can be grown with high crystalline quality nearly lattice matched with GaAs, thus making commercial production relatively simple; thirdly, because of the relatively large bandgap of In0.5Ga0.5P, it should enable large cell conversion efficiencies and operation at elevated temperatures without cooling (due to low thermally generated leakage currents); fourthly, it should be tolerant to high doses of radiation [18].

This paper describes the electrical performances of an 63Ni In0.5Ga0.5P betavoltaic cell over the temperature range −20 °C and 100 °C. The results show the dependence on temperature of the open circuit voltage, the short circuit current, the maximum output power, and the cell internal conversion efficiency. The 63Ni In0.5Ga0.5P betavoltaic cell, due to the high In0.5Ga0.5P attenuation coefficients, produced higher output power with respect to that produced by the previously published AlInP betavoltaic cell [8], at each temperature studied; it has to be noted that the In0.5Ga0.5P converter reported has also a thicker i-layer with respect to the previously used AlInP converter photodiode. The exceptional results obtained are also a consequence of the high performances of the In0.5Ga0.5P detector produced; the crystalline quality of the studied In0.5Ga0.5P structure is very high in comparison to other commonly studied wide bandgap material structures (e.g. GaN) due to the advanced growth and fabrication technique used.

2. Materials and methods

A p⁺–i–n⁺ (5 µm i-layer) In0.5Ga0.5P layer structure was grown on a n⁺ GaAs substrate, using metalorganic vapour phase epitaxy. In order to suppress CuPt type ordering and associated decrease of the bandgap energy of In0.5Ga0.5P [22–24], the substrate’s epitaxial surface had a miscut angle of 10° towards (1 1 1)A. The details of the In0.5Ga0.5P structure and the metallisation layers are summarised in table 1. Chemical wet etching techniques were used to fabricate a 400 µm diameter In0.5Ga0.5P mesa photodiode: 1:1:1 K2Cr2O7:HBr:CH3COOH solution was used as the etchant, followed by a 10 s finishing etch in a 1:8:80 H2SO4:H2O2:H2O solution. The top Ohmic contact had an annular shape with bondpad, the top metallisation covered 33% of the In0.5Ga0.5P device’s top face.

| Layer | Material | Thickness (µm) | Dopant | Dopant type | Doping density (cm⁻²) |
|-------|----------|----------------|--------|-------------|----------------------|
| 1     | Ti       | 0.02           |        |            |                      |
| 2     | Au       | 0.2            |        |            |                      |
| 3     | GaAs     | 0.01           | Zn     | p⁺         | 1 × 10¹⁰             |
| 4     | In0.5Ga0.5P | 0.2       | Zn     | p⁺         | 2 × 10¹⁸             |
| 5     | In0.5Ga0.5P | 5         |        |            |                      |
| 6     | In0.5Ga0.5P | 0.1   | Si     | n⁻         | 2 × 10¹⁸             |
| 7     | Substrate | n⁺ GaAs       |        |            |                      |
| 8     | Au       | 0.2            |        |            |                      |
| 9     | InGe     | 0.02           |        |            |                      |

Table 1. Layer details of the In0.5Ga0.5P diode.

The In0.5Ga0.5P mesa diode was illuminated by a standard laboratory 185 MBq 63Ni radioisotope beta source, which was positioned as close as experimentally possible (3 mm) to the top of the In0.5Ga0.5P device in order to maximize the energy deposited by the electrons in the converter device. It has to be noted that 185 MBq was the actual activity of the source; in a best case scenario (i.e. specific activity of 56 mCi mg⁻¹) such a source would have an apparent activity of 172 MBq taking into account self-absorption effects [25]. The 63Ni radioisotope beta source was a Ni foil (7 mm by 7 mm) with 63Ni on one side; to comply with local radiation rules the source had a 1 µm layer of inactive Ni electroplated over the active 63Ni, such that it could be handled as a sealed source. Both the In0.5Ga0.5P detector and the 63Ni radioactive source were placed inside a temperature test chamber (TAS Micro MT); dry nitrogen was constantly flowing inside the chamber to prevent any humidity related effects influencing the measurements (environment relative humidity <5%).

The Monte Carlo computer modeling package CASINO (version 3.3) [26, 27] was used to study the beta particle quantum efficiency of the In0.5Ga0.5P device in the energy range of interest (1 keV to 66 keV). 4000 beta particles were used in each simulation, the beta particles were injected at the p⁺-side of the In0.5Ga0.5P structure. At each electron energy, two slightly different structures were simulated: firstly, we simulated the In0.5Ga0.5P structure without a top metal contact; secondly, we simulated the In0.5Ga0.5P structure with a top metal contact covering all the device surface. A total of 132 simulations were run. Each simulation gave information of where the beta electrons are absorbed in the In0.5Ga0.5P structure; the percentage (QE) of the electron energy absorbed through the 5 µm i-layer In0.5Ga0.5P device with respect to the electron energy incident on the face of the cell was quantified. Quantum efficiency values for the structure without a top metal contact (QE纰) and for the structure with a top metal contact (QE mũi) were obtained. Since the top metal contact only covered 33% of the device surface, the percentage (QE纰) of the energy deposited by beta electrons of various energy in the In0.5Ga0.5P i-layer was calculated from a weighted sum of QE纰 and QE mũi; the calculated QE纰 are shown in figure 1.

Following the simulations of the beta particle quantum efficiency of the device, modelling was conducted to simulate the
attenuation of the beta electrons through the protective inactive Ni over-layer (1 μm thick) of the specific radioisotope beta particle source use in the experimental characterizations. It was found that the beta electrons with energies < 20 keV were primarily attenuated by the inactive Ni over-layer. If a real-world betavoltaic battery were to be made, the inactive Ni over-layer would not be present, but for the purposes of the semiconductor device characterisation reported here the over-layer was necessary to comply with laboratory safety protocols. Attenuation of the beta particles in the dry nitrogen gap (3 mm) was determined to be negligible compared to the other losses.

The expected electrical power \( P_{\text{in}} \) extracted from the In0.5Ga0.5P betavoltaic cell was calculated according to equation (1):

\[
P_{\text{in}} = \sum_{i=0}^{\text{endpoint}=66} \frac{A}{2} E_{\text{mi}} \frac{A_{\text{InGaP}}}{A_{\text{Ni}}} \frac{\text{QE}_i}{\text{ω}_{\text{InGaP}}} \times 1.6 \times 10^{-19} \tag{1}
\]

where \( A \) was the apparent activity of the \( ^{63}\text{Ni} \) source (172 MBq, under the approximation of an highly pure \( ^{63}\text{Ni} \) radioactive source), \( E_{\text{mi}} \) was the emission probability of an electron of energy \( i \) after taking into account self-absorption effects, \( A_{\text{Ni}} \) was the area of the \( ^{63}\text{Ni} \) source, \( A_{\text{InGaP}} \) was the area of the In0.5Ga0.5P detector, \( \text{QE}_i \) was the percentage of each electron energy absorbed in the In0.5Ga0.5P i-layer considering also attenuation through the protective inactive Ni over-layer, \( \text{ω}_{\text{InGaP}} \) the In0.5Ga0.5P electron–hole pair creation energy (4.8 eV, 2.5 times the bandgap). Due to the source-detector system geometry, only half of the beta electrons were emitted towards the In0.5Ga0.5P device; thus, the apparent activity of the \( ^{63}\text{Ni} \) radioactive source was halved for use in equation (1). \( P_{\text{in}} \) was found to be 26 pW. It should be noted that a best case scenario (highly pure \( ^{63}\text{Ni} \)) was assumed here in order to produce the most conservative (pessimistic) betavoltaic efficiencies in section 3.

### 3. Results and discussion

A Keithley 6487 picoammeter/voltage source was used to measure the current across the In0.5Ga0.5P diode as function of applied forward bias; the voltage range studied was from 0 V to 1 V (in 0.01 V increments). The uncertainty associated with a single reading was 0.3% of its value plus 400 fA, while the uncertainty associated with the applied biases was 0.1% of their values plus 1 mV [28]. Preliminary dark current measurements as a function of forward bias were performed on the In0.5Ga0.5P device over the temperature range −20 °C to 100 °C, and shown in figure 2. The decreased dark current observed at −20 °C, with respect to the one observed at 100 °C, could be attributed to the lower thermal energy available at lower temperatures. Because of the dependence between dark current and applied forward bias in a simple p–n diode \( I = I_0 \exp\{qV/nkT\} \) [29], it was possible to calculate the saturation current and the ideality factor of the In0.5Ga0.5P device at each temperature: the relation between the dark current and the applied forward bias was linearised as \( \ln I = A + BV \) and a linear least square fitting was used to find \( A = \ln I_0 \) and \( B = q/(nkT) \). The logarithm of the measured saturation current and the calculated ideality factor as a function of temperatures are shown in figures 3(a) and (b), respectively. It was found that the saturation current and the ideality factor decreased as a function of temperature; an ideality factor > 1.5 was obtained at all the temperatures studied, highlighting that the generation-recombination mechanism was dominant over the diffusion mechanism [29].

Current characteristics as a function of applied forward bias were then measured under the illumination of the \( ^{63}\text{Ni} \) radioisotope beta particle source in the temperature range −20 °C and 100 °C. Figure 4 shows the illuminated current as a function of forward bias for the In0.5Ga0.5P device at the temperatures studied. It can be observed that the shape of the experimental curves differed at temperature below 40 °C, this may be due to the conductive mechanism not being negligible with respect to the thermal mechanism (scattering) at low temperatures. The conductive contribution may be responsible for changes in the material resistance due to the increase number of carriers generated as the beta electrons deposit their energy along their tracks in the In0.5Ga0.5P structure.
The interception points of the illuminated curves on the horizontal and vertical axes corresponded to the open circuit voltage and the short circuit current, respectively. The dependence of such parameters on temperature is shown in figures 5 and 6. The open circuit voltage (\(V_{OC}\)) decreased linearly with increased temperature; in figure 5, the linear least square fit performed on the experimental data is also shown. The variation of the open circuit voltage with temperature was found to be \(dV_{OC}/dT = (0.00368 \pm 0.00013) \text{ V}^\circ \text{C}^{-1}\). The In\(_{0.5}\)Ga\(_{0.5}\)P device illuminated with the \(^{63}\)Ni radioisotope beta particle source had higher \(V_{OC}\) values with respect to those previously reported for an Al\(_{0.52}\)In\(_{0.48}\)P \(^{63}\)Ni radioisotope betavoltaic cell [8]: at \(-20^\circ\text{C}\), for example, an open circuit voltage of 0.69 V was observed in the \(^{63}\)Ni–In\(_{0.5}\)Ga\(_{0.5}\)P cell, whilst 0.52 V was measured in the \(^{63}\)Ni–Al\(_{0.52}\)In\(_{0.48}\)P cell. This may be explained by the different thicknesses of the In\(_{0.5}\)Ga\(_{0.5}\)P (5 \(\mu\text{m}\) i-layer) and Al\(_{0.52}\)In\(_{0.48}\)P (2 \(\mu\text{m}\) i-layer) devices; the beta-generated carrier density may have been lower in the thicker In\(_{0.5}\)Ga\(_{0.5}\)P leading to a less significant conductive effect.

The short circuit current (\(I_{SC}\)) increased linearly as the temperature was reduced from 100 \(^\circ\text{C}\) to 40 \(^\circ\text{C}\), whilst it saturated (~4.5 \(\text{pA}\)) at temperatures below 40 \(^\circ\text{C}\). A similar behaviour was observed in an Al\(_{0.52}\)In\(_{0.48}\)P \(^{63}\)Ni radioisotope betavoltaic cell [8]. The short circuit current was found to be dependent on the carrier diffusion length and the number of generated carriers: at increased temperature, while the carrier diffusion length decreased due to the higher phonon scattering, the number of generated carrier increased because of the lower electron–hole pair creation energy. The observed decrease of the short circuit current at higher temperatures from 40 \(^\circ\text{C}\) to 100 \(^\circ\text{C}\) may be attributed to a larger decrease in the carrier diffusion length rather than the increase in the number of generated carriers. The approximately constant value assumed by the short circuit current between \(-20^\circ\text{C}\) and 40 \(^\circ\text{C}\) may be explained considering that the conductive mechanism decreased the semiconductor resistance: in such circumstance the decrease in the carrier diffusion lengths (affected by the change in resistance) was possibly compensated by the increase of the number of carriers generated. The conductive mechanism was particularly evident at low temperature and low applied forward bias.
The cell output power ($P$), calculated as $P = IV$, is shown in figure 7. Increasing the forward bias applied, the output power increased to a maximum ($P_m$) and then decreased. Figure 8(a) shows the maximum output powers extracted from the In$_{0.5}$Ga$_{0.5}$P illuminated with the $^{60}$Ni radioisotope beta particle source at temperatures between $-20$ °C and 100 °C; $P_m$ increased at decreased temperatures, this can be explained considering its dependence on the open circuit voltage [29]. A maximum output power of 0.92 pW, corresponding to 1.2 $\mu$W/Ci (ratio between the maximum output power, 0.92 pW, and the number of electrons expected on the detector taking into account the effects of the inactive Ni overlayer, $2.9 \times 10^5$ s$^{-1} = 7.8 \times 10^{-6}$ Ci), was extracted at $-20$ °C. Figure 8(b) shows the internal conversion efficiency ($\eta$) values calculated at the different temperatures studied; the internal conversion efficiency was obtained by dividing $P_m$ with $P_{th}$, the value of which (26 pW) was estimated in section 2. $\eta$ increased at decreased temperatures, with a value of $\sim 4\%$ being observed at $-20$ °C.

The maximum output power ($P_m$) values were higher than the ones observed using an Al$_{0.52}$In$_{0.48}$P $^{60}$Ni radioisotope betavoltaic cell [8]: at $-20$ °C, for example, $P_m$ of 0.92 pW were found here, whilst $P_m$ of 0.28 pW were obtained for the Al$_{0.52}$In$_{0.48}$P $^{60}$Ni radioisotope betavoltaic cell. The linear dependence of the output power from the open circuit voltage explained the difference in the results reported here from that reported in the Al$_{0.52}$In$_{0.48}$P $^{60}$Ni radioisotope betavoltaic [8] cells. It should also be noted that the i-layer thickness of the In$_{0.5}$Ga$_{0.5}$P structure was 5 $\mu$m, whilst the i-layer thickness of the Al$_{0.52}$In$_{0.48}$P device was just 2 $\mu$m. The InGaP betavoltaic conversion efficiency was higher than those observed for other wide bandgap semiconductors, including GaAs [13] and Al$_{0.52}$In$_{0.48}$P [8], particularly at high temperatures. Such conversion efficiency improvement was less evident at lower temperatures, where conductive mechanisms degraded the cell performance.

Improved output power would be expected using a thicker cell and a custom sized $^{60}$Ni radioisotope beta source without the inactive Ni over-layer (the ratio between the area of the device, 0.13 mm$^2$, and the area of the radioactive $^{60}$Ni source, 49 mm$^2$, was 0.0026). The use of another In$_{0.5}$Ga$_{0.5}$P $^{60}$Ni radioisotope betavoltaic cell, placed on top of a $^{60}$Ni radioisotope betavoltaic cell, showed a complementary improvement in output power.
beta source with two active sides, would also be helpful in order to maximise the conversion of beta energy in electrical energy. Such design improvements will be considered for future generations of radioisotope microbatteries from our laboratory. Next generation of In$_{0.5}$Ga$_{0.5}$P $^{63}$Ni radioisotope betavoltaic cells will also aim to suppress conductive mechanisms such to exploit the properties (e.g. high linear attenuation coefficient, high bandgap) that make In$_{0.5}$Ga$_{0.5}$P attractive as converter layer in betavoltaic microbattery.

4. Conclusions

This paper is the first demonstration of a temperature tolerant In$_{0.5}$Ga$_{0.5}$P $^{63}$Ni betavoltaic cell. A p$^+-i$–n$^+$ (5 µm i-layer) In$_{0.5}$Ga$_{0.5}$P mesa diode was illuminated by a 185 MBq $^{63}$Ni radioisotope beta source; the temperature range across which the In$_{0.5}$Ga$_{0.5}$P betavoltaic cell was characterised was −20 °C to 100 °C. The electrical performance of the In$_{0.5}$Ga$_{0.5}$P cell was analysed as a function of temperature; the open circuit voltage ($V_{OC}$) was saturated to a value of ~4.5 pA at temperatures <40 °C. The electrical performance of the In$_{0.5}$Ga$_{0.5}$P cell showed better performance than that of an Al$_{0.52}$In$_{0.48}$P $^{63}$Ni betavoltaic cell [8], most likely as a consequence of the thicker In$_{0.5}$Ga$_{0.5}$P structure (5 µm i-layer) used here compared with the earlier Al$_{0.52}$In$_{0.48}$P devices (2 µm i-layer).

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Data Statement

Data underlying this work are subject to commercial confidentiality. The authors regret that they cannot grant public requests for further access to any data produced during the study.

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