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Measurement of the electron–hole pair creation energy in $Al_{0.52}In_{0.48}P$ using X-ray radiation

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ABSTRACT

The average energy consumed in the generation of an electron–hole pair (ε_{AlInP}) in $Al_{0.52}In_{0.48}P$ was experimentally measured across the temperature range −20 °C to 100 °C, using a custom AlInP X-ray-photodiode, an ^{55}Fe radioisotope X-ray source, and custom low-noise charge-sensitive preamplifier electronics. ε_{AlInP} was found to linearly decrease with increasing temperature according to the equation ε_{AlInP} = (-0.0033 eV/K ± 0.0033 eV/K)T + (6.31 eV ± 0.10 eV). At room temperature (20 °C), ε_{AlInP} = 5.34 eV ± 0.07 eV.

1. Introduction

Photon counting X-ray spectrometers that can operate in harsh environments (high temperature, intense radiation) are increasingly important for extreme terrestrial and space exploration applications. Wide bandgap semiconductors, such as GaAs [1,2], AlGaAs [3], and SiC [4], have been investigated as detector materials for such X-ray spectrometers. Compared to narrower bandgap semiconductors, such as Si, wide bandgap materials have the advantage of being able to operate at elevated temperatures without cooling systems due to their smaller thermally generated currents.

Recently, $Al_{0.52}In_{0.48}P$ photon counting X-ray spectrometers have been demonstrated for the first time in non-avalanche [5] and avalanche [6] modes. $Al_{0.52}In_{0.48}P$ has an indirect bandgap of 2.31 eV [7]; $Al_xIn_{1-x}P$ with different Al fractions correspond to different bandgaps: in principle, the Al fraction can vary from 0, corresponding to a bandgap of 2.5 eV (in this case it reduces to the binary compound InP), to 1, corresponding to a bandgap of 1.34 eV (in this case it reduces to the binary compound AlP). Due to its bandgap, $Al_{0.52}In_{0.48}P$ devices present low thermally generated leakage currents even at high temperatures [5,8]. $Al_{0.52}In_{0.48}P$ has a high effective atomic number, and hence relatively high linear X-ray attenuation coefficient, as a consequence of the presence of Indium (atomic number 49) [9]. This results in higher X-ray quantum efficiency per unit thickness [5] compared to some other wide bandgap X-ray photodetectors, e.g. SiC, AlGaAs, and GaAs [10,11]. $Al_{0.52}In_{0.48}P$ is nearly lattice matched with commercially available GaAs substrates and can be grown with high crystalline quality. The ability to more easily control the doping in $Al_{0.52}In_{0.48}P$ with respect to some II–VI semiconductors [12] is also beneficial. All these characteristics make $Al_{0.52}In_{0.48}P$ highly promising for future X-ray and γ-ray detectors. Although $Al_{0.52}In_{0.48}P$ has received significant research attention at optical wavelengths, e.g. as a barrier material in quantum well structures [13,14], cladding layers in laser diodes [15,16], optical windows in solar cells [17], blue–green optical detectors [7,18] etc., many material properties have not yet been reported; this is particularly true for properties related to the compound's use in X-ray, γ-ray, and charged particle detection. Measurements of the average energy consumed in the generation of an electron–hole pair (ε_{AlInP}) and the Fano factor (F), for example, have not yet been reported, despite the knowledge of ε_{AlInP} and F being important since they determine the statistically limited energy resolution of an X-ray detector [19].

The fundamental statistically limited energy resolution in terms of Full Width at Half Maximum (FWHM, in eV) of a non-avalanche semiconductor detector is given by:

$$FWHM[\mathrm{eV}] = 2.35\varepsilon\sqrt{\frac{FE}{\varepsilon}} \quad (1)$$

where ε is the semiconductor's electron–hole pair creation energy, F is the semiconductor's Fano factor, and E is the X-ray photon's energy.

It must be underlined that the energy consumed in the generation of an electron–hole pair at X-ray energies in a semiconductor differs from its bandgap; whilst the $Al_{0.52}In_{0.48}P$ bandgap is well known [7], until now there have been no experimental measurements of ε_{AlInP}.

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Table 1
Layer details of the $Al_{0.52}In_{0.48}P$ X-ray photodiode.

Layer	Material	Thickness (μm)	Dopant	Dopant type	Doping density (cm^{-3})
1	Ti	0.02			
2	Au	0.2			
3	GaAs	0.01	Zn	P^+	1×10^{19}
4	$Al_{0.52}In_{0.48}P$	0.2	Zn	P^+	5×10^{17}
5	$Al_{0.52}In_{0.48}P$	2	Undoped		
6	$Al_{0.52}In_{0.48}P$	0.1	Si	n^+	2×10^{18}
7	Substrate n^+ GaAs				
8	InGe	0.02			
9	Au	0.2			

Table 2
Layer details of the GaAs X-ray photodiode.

Layer	Material	Thickness (μm)	Dopant	Dopant type	Doping density (cm^{-3})
1	Ti	0.02			
2	Au	0.2			
3	GaAs	0.5	Be	P^+	2×10^{18}
4	GaAs	10	Undoped		$<10^{15}$
5	GaAs	1	Si	n^+	2×10^{18}
6	Substrate n^+ GaAs				
7	InGe	0.02			
8	Au	0.2			

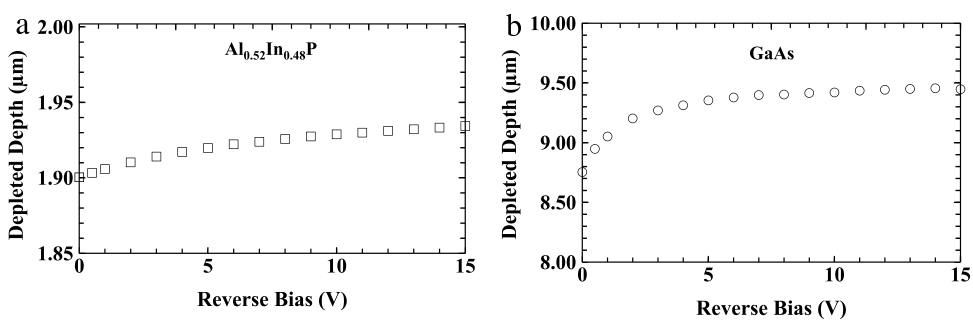

Fig. 1. Depletion depth as a function of applied reverse bias at room temperature (a) for the $Al_{0.52}In_{0.48}P$ device (empty squares), and (b) for the GaAs devices (empty circles).

2. Results

Firstly, the average energy consumed in the generation of an electron–hole pair (commonly called the electron–hole pair creation energy) in $Al_{0.52}In_{0.48}P$ (ε_{AlInP}) was measured at room temperature (20 °C), using a custom $Al_{0.52}In_{0.48}P$ X-ray photodiode, an ^{55}Fe radioisotope X-ray source, custom low-noise charge-sensitive preamplifier electronics, and a high-purity reference GaAs X-ray photodiode. The method used was similar to that used by other researchers to determine the electron–hole pair creation energies for GaAs, SiC, $Al_{0.8}Ga_{0.2}As$, and $Al_{0.2}Ga_{0.8}As$ [20–23]: the electron–hole pair creation energy for $Al_{0.52}In_{0.48}P$ was experimentally determined by measuring the amount of charge created by the absorption of X-rays from an ^{55}Fe radioisotope X-ray source (Mn Kα: 5.9 keV; Mn Kβ: 6.49 keV) in the $Al_{0.52}In_{0.48}P$ photodiode relative to that created in GaAs [20–23].

A 200 μm diameter mesa $Al_{0.52}In_{0.48}P$ photodiode was grown by metalorganic vapour phase epitaxy (MOVPE) on a (100) n-GaAs: Si substrate with a misorientation of 10 degrees towards ⟨111⟩A to suppress the CuPt-like ordered phase [24]. The $Al_{0.52}In_{0.48}P$ structure is summarised in Table 1. Preliminarily characterisation of the $Al_{0.52}In_{0.48}P$ photodiode was performed to ensure its suitability for the measurements [5]. A well characterised high-purity 200 μm diameter mesa GaAs photodiode [25] was used as the GaAs reference detector; the structure of which is summarised in Table 2. It has to be noted that both the $Al_{0.52}In_{0.48}P$ and the GaAs devices were P–i–n structures.

The $Al_{0.52}In_{0.48}P$ photodiode was connected in parallel with the GaAs reference detector, to a custom-made low-noise charge-sensitive preamplifier of feedback resistorless design, similar to Ref. [26]. The output of the preamplifier was connected to an Ortec 572a shaping amplifier and then to a multichannel analyser (MCA). An ^{55}Fe radioisotope X-ray source was positioned, in turn, above of each of the $Al_{0.52}In_{0.48}P$ and GaAs mesa photodiodes (5 mm away from the photodiodes' surface in each case). Measurements were taken at room temperature when both detectors were reverse biased at 10 V (electric field strength across the $Al_{0.52}In_{0.48}P$ detector of 50 kV/cm): preliminary results had shown that both the $Al_{0.52}In_{0.48}P$ and GaAs detectors were fully depleted at 10 V (Figs. 1 and 2 report the calculated depletion region and the expected carrier concentrations for both the $Al_{0.52}In_{0.48}P$ [5] and the GaAs detectors [25]), and exhibited negligible charge trapping in this bias condition. Spectra were accumulated with the ^{55}Fe radioisotope X-ray source illuminating the $Al_{0.52}In_{0.48}P$ and GaAs devices in turn. The X-ray photopeaks were each the combination of the Mn Kα and Mn Kβ lines from the ^{55}Fe radioisotope X-ray source. Gaussians were fitted to the photopeak obtained with each detector taking into account the relative X-ray emission rates of the ^{55}Fe radioisotope X-ray source [27] and the relative differences in efficiency of the detectors at these X-ray energies. Energy resolutions (FWHM) at 5.9 keV of 1.32 keV and 1.09 keV were measured when the ^{55}Fe radioisotope X-ray source was illuminating the $Al_{0.52}In_{0.48}P$ and the GaAs devices, respectively. These values were larger than those measured when the detectors were individually connected to the preamplifier i.e. 960 eV FWHM at 5.9 keV with the $Al_{0.52}In_{0.48}P$ detector [5] and 660 eV FWHM at 5.9 keV with the GaAs detector [25] both at room temperature. Broadened energy resolutions were observed in the present case because the $Al_{0.52}In_{0.48}P$ and the GaAs photodiodes were connected in parallel with each other to the preamplifier. The detector capacitances (2.4 pF for the $Al_{0.52}In_{0.48}P$ detector, and 1.10 pF for the GaAs detector) and leakage currents (0.19 pA for the $Al_{0.52}In_{0.48}P$ detector, and 4.4 pA for the GaAs detector) summed, resulting in