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Review

HgCdTe avalanche photodiodes: A review

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ABSTRACT

This paper presents a comprehensive review of fundamental issues, device architectures, technology development and applications of HgCdTe based avalanche photodiodes (APD). High gain, above 5×10^3, a low excess noise factor close to unity, THz gain-bandwidth product, and fast response in the range of pico-seconds has been achieved by electron-initiated avalanche multiplication for SWIR, MWIR, and LWIR detector applications involving low optical signals. Detector arrays with good element-to-element uniformity have been fabricated paving the way for fabrication of HgCdTe-APD FPAs.

Contents

1. Introduction

Avalanche photodiodes are useful for the detection of low power optical signals in the space based as well as terrestrial thermal imaging applications. Infrared avalanche photodiodes (APDs) with high bandwidth (BW) and internal gain are suited for the detection of attenuated optical signals as in battle field conditions and long range applications. Better control over the growth of multilayer HgCdTe epi-structures by MBE has led to development of a new generation of high sensitive II–VI avalanche photodiodes. Under the influence of a high electric field, the electrons/holes in the depletion region of an APD are accelerated and gradually acquire sufficient kinetic energy to impact ionize other electrons/holes leading to the junction breakdown [1,2]. It results in current gain with a low noise. The multiplication region of APD is important to achieve good avalanche gain with low multiplication noise and high bandwidth. Multiplication

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noise and gain-bandwidth (GBW) product of APD are determined by the ionization coefficient of electrons (α_e) and holes (α_h) in the multiplication region, which are the characteristics of the material [3].

APDs fabricated with Si and III–V semiconductors such as InGaAs/InP, InAs, InAlAs (from 0.3 to 1.1 μm), Ge (from 0.8 to 1.6 μm), and InGaAs (from 0.9 to 1.7 μm) show high excess noise at high gain values as both types of carriers are involved in the multiplication process. In these groups III–V or IV semiconductors, both electrons and holes contribute to the multiplication process due to the high multiplication rate. High reverse bias is needed to initiate the avalanche process in these materials. The evacuation rate of charge carriers from the depletion region is also slow [1,4–9]. The excess noise factor (F) is reported to be in the range 4–5 for III–V materials and 2–3 for Si. Participation of both types of carriers in the multiplication process is known to yield higher excess noise. Bandwidth of III–V APDs is in the range 300–400 GHz [8]. AlGaN is also a promising material for fabrication of ultraviolet (UV) APDs because of its direct band gap. But it is also characterized by a low gain at high reverse bias and hence low responsivity compared to other UV-APD materials [5,10]. Feasibility of fabricating InAs, InAsSb, or InAlSb based APDs have also been explored by many groups. InAsSb is used in low power, high frequency applications in long-wave and mid-wave infrared region. InAsSb has some advantages over other materials such as its narrow band gap, availability of high quality, low cost substrates, and high electron mobility [5,11–13].

HgCdTe is an industry standard material for the fabrication of infrared detectors for critical and strategic applications covering the important IR range from 1.3 to 16 μm. Asymmetry between the effective mass of electrons in the conduction band and heavy holes results in an unequal ionization coefficient for electron and hole in HgCdTe. HgCdTe has a highly favorable electron to hole impact ionization ratio for different compositions from $x=0.1$ to 0.7. High avalanche gain can be achieved with low noise as the multiplication process is initiated by a single carrier; electron injection for lower x-values ($x<0.6$) or hole injection for $0.6<x<0.7$ [14–20]. The dominant carrier multiplication process can be limited to one type of carriers in HgCdTe based APDs. Bandwidth is independent of gain in the case of electron injected APDs (e-APDs) [19]. High gain with bandwidth in the range of THz has been achieved with a low excess noise even at low reverse bias in HgCdTe e-APDs [8]. Excess noise close to unity is achievable in this material. HgCdTe APDs offer high internal gain, high quantum efficiency and sensitivity, low dark current, low excess noise, and fast response time because of its narrow band gap.

Initial development efforts in HgCdTe APDs were limited to the SWIR region for telecommunication applications [21–27]. Shin et al. [21] reported the fabrication of a planar HgCdTe/CdTe APD ($\lambda_c=1.22$ μm). Avalanche gain of 15 at 1.06 μm under a reverse bias of 80 V was reported. Planar implanted n-on-p photodiode with a gain of 5 under 10 V reverse bias and bandwidth 650 MHz were achieved by Alabedra et al. [22]. Planar p–i–n $Hg_{0.56}Cd_{0.44}Te$ APD in 1.6–2.5 μm range was also demonstrated using electron and hole injection multiplication processes separately and concluded that (i) electron injection yields relatively lower excess noise factor as compared to hole injection and (ii) hole-initiated APD requires higher reverse bias to initiate the avalanche process [24]. Hall et al. [16] also concurred with these results. de Lyon et al. [27] exhibited a gain of 30–40 under up to 90 V reverse bias at 300 K in the MBE grown APD employing hole impact ionization resonance condition. Impact ionization in LWIR photodiodes was first reported by Elliott et al. [28], followed by Beck et al. [29], and Vaidyanathan et al. [30]. Salient results of Elliott et al. included demonstration of lateral collection loop hole diodes in LWIR at liquid nitrogen temperature. It was also noticed that impact ionization process was sustained by the multiplication of electrons. Maximum gain of 5.9 under 1.4 V reverse bias was achieved [28]. Beck et al. pioneered the electron-initiated avalanche process in MWIR HgCdTe lateral-collection p-around-n photodiode with p-type absorber region at 77 K temperature and showed that (i) avalanche gain increases exponentially with reverse bias voltage, (ii) it is uniform from element to element in an array, and (iii) noise less gain 50 can be achieved at normal reverse bias [19,29]. Kinch et al. [20] proposed a theory explaining the physics behind electron-initiated HgCdTe avalanche photodiode on the basis of unequal ionization coefficient of electron and hole owing to its band structure . Some features of this theory are further elaborated in Section 2.2. Vaidyanathan et al. reported a higher gain of about 100 (at 3.5 V bias, 77 K) in LWIR e-APD. They fabricated 1×64 n^+–n–p planar double layer planar hetero-structure (DLPH) arrays [30]. Beck et al. [19] and Kinch et al. [20] fueled many demonstrations of HgCdTe electron-initiated APDs in variety of configurations and architectures [31–37]. General consensus is that electron-initiated avalanche photodiode (e-APD) is more favorable in SWIR, MWIR, and LWIR regions in terms of high gain with low noise even at nominal reverse bias and high speed as compared to the hole-initiated case. Back-illuminated planar n-on-p e-APDs were also fabricated by Reine et al. [35] on LPE grown HgCdTe having acceptor of 2×10^{16} cm^{-3}. They reported a higher gain of 648 (-11.7 V, 77 K, and 4.06 μm) [35]. Rothman et al. [8] improved the gain to 5300 (-12.5 V) with a lower noise factor of 1.0–1.3, and lower dark current in planar p–i–n 30×30-μm^2 photodiodes with a cutoff wavelength of 5.0 μm at 77 K. This is the highest reported gain for HgCdTe e-APD. Perrais et al. [37] of the same group demonstrated gain of 2800 (-12 V, 77 K, and 5.3 μm), nearly constant RC time constant limited band width of 400 MHZ and a record high gain band width product, GBW$=$2.1 THz in front-illuminated HgCdTe MWIR e-APD.

One can see that feasibility of high gain ($\sim 5\times 10^3$) achievable at low bias, low noise factor (F is close to unity), high GBW product (the highest reported $\sim$2.1 THz) and very short integration time $\sim$70 ps make HgCdTe APD to be one of the most promising paths to focal plane arrays for low flux and high speed applications such as active and hyper-spectral imaging. It can be used in passive mode for large field surveillance, and in the active gated 2D or 3D mode for identification. HgCdTe enabled arrays are also being used for eye safe applications in LADAR/LIDAR, which can be operated at room temperature [38–42]. HgCdTe has fundamental properties and favorable band structure conducive to producing excellent detectors. High gain at low bias, extremely low noise, high gain-bandwidth product, faster response time and gain independent bandwidth achievable in HgCdTe APD are suited for integration in the next generation FPAs. These features have an edge over the III–V compound based APD FPAs.

Several groups including DRS Technologies, CEA-LETI, BAE systems are working on the development of HgCdTe based APDs. New applications such as active and passive amplified imaging that require high sensitivity and/or fast detection have been possible with the advent of high performance HgCdTe based APDs. An attempt has been made to include the results achieved by the leading groups working in the field. Theory, operating principles, design/architectures, fabrication technology and applications of HgCdTe based APDs are covered in this paper.

2. Device design

An APD generally consists of a heavily doped p type absorption region A and a lightly doped n^- type multiplication region M shown in Fig. 1. Width of the depletion region formed in the n-region increases continuously with increasing reverse bias until the field is sufficient to create avalanche multiplication. This region starts acting as a multiplication zone. The p-region surrounding it