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AlGaAsSb Avalanche Photodiodes

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***Abstract*—Avalanche photodiodes are widely used in optical receivers for high-speed communication systems. We have been studying the material AlGaAsSb (lattice-matched to InP substrates) experimentally in recent years, evaluating its potential as an alternative avalanche material for these avalanche photodiodes. Our experimental studies cover key characteristics relevant to high-speed avalanche photodiodes. The data obtained show that the material AlGaAsSb has higher gain-bandwidth product, lower excess noise factors, and weaker temperature dependence, compared to current avalanche materials such as InP and InAlAs.**

Keywords—avalanche photodiodes, bandwidth, excess noise, temperature.

I. INTRODUCTION

Avalanche Photodiodes (APDs) sensitive to 1.31 and 1.55 μm wavelengths light are essential components of optical communication systems. Appropriately designed APDs provide appreciable avalanche gain, an end result of successive impact ionization events that occur in the avalanche regions within the devices. When an APD is used in a high-speed optical receivers, whose noise is usually dominated by its amplifier's noise, the internal gain from the APD improves the overall signal-to-noise ratio. Thus a given bit-error-rate can be achieved with a lower optical signal power.

A typical APD for near infrared light consists of an $In_{0.53}Ga_{0.47}As$ layer (lattice-matched to InP substrates) and an InP avalanche layer, to absorb the near infrared light and to provide sufficient avalanche gain, respectively. Doping profile of the APD will have been designed to achieve low and high electric field, within the absorption layer and the avalanche layer, respectively. Assuming that the APD has an appropriate doping profile, many of the APD's key parameters, are determined by the impact ionization properties of the material used in the avalanche layer. For optical communication systems, the key APD performance parameters include excess noise characteristics, gain-bandwidth product (GBP), temperature dependence of avalanche gain, and dark current.

Researchers have been exploring a number of semiconductor materials, evaluating their impact ionization properties for application in near infrared APDs and developing prototype APDs using novel avalanche materials. There have been major investigations on $In_{0.52}Al_{0.48}As$ (on InP substrates) [1], $Al_{1-x}Ga_xAs$ [2] (on GaAs substrates, with InGaAsN as the potential absorption material [3]), $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ (on InP substrates) [4], and $Al_{1-x}In_xAs_ySb_{1-y}$ [5] (on GaSb substrates). At present, only the materials $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ and $Al_{1-x}In_xAs_ySb_{1-y}$ are being actively investigated, mainly because they have shown greater potential as avalanche materials, compared to InP and $In_{0.52}Al_{0.48}As$. In this presentation, we summarize our data on important impact ionization properties of $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ APDs obtained so far.

II. GAIN-BANDWIDTH PRODUCT

One of the most important performance parameters for APDs used in optical receivers is their GBP. When the avalanche gain is large, upper limits of GBP exist for most APDs. Building up the desired avalanche gain generally requires multiple carrier transits, increasing the avalanche current duration and limiting the APD bandwidth. To increase these upper limits, one could use very thin avalanche layers, which minimize carrier transit times. This method is however constrained by onset of band-to-band tunneling currents from the avalanche layer, where very high electric field exists. The upper GBP limits are consequently estimated to be ~ 180 and 220 GHz, for InP and $In_{0.52}Al_{0.48}As$ APDs, respectively [6].

Since the material system $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ has large, indirect bandgaps to reduce tunneling current, an APD using an $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ avalanche layer is expected to have a higher GBP limit. We demonstrated an APD with an $In_{0.53}Ga_{0.47}As$ absorption layer and a thin (100nm) $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ (indirect bandgap of 1.56 eV) avalanche layer. The APD, grown on semi-insulating InP substrate, exhibited a GBP of 424 GHz [4], exceeding previous values reported for InP-compatible APDs, as compared in Fig. 1.

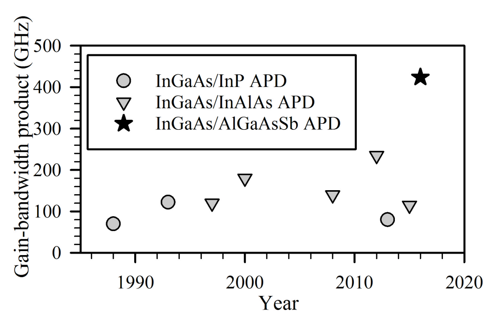

Fig. 1. Comparison of the GBP obtained from our $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ APD [4] with typical experimental GBP values from APDs with InP and $In_{0.52}Al_{0.48}As$ avalanche layers.

III. EXCESS NOISE CHARACTERISTICS

Although the avalanche gain from an APD can improve the optical receiver's signal-to-noise ratio, considerations must be given to penalty associated with avalanche noise of the APD,

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which is characterized by the excess noise factor. Hence careful measurements of excess noise factors versus avalanche gain using appropriate carrier injection conditions are crucial, when evaluating potential avalanche materials.

Our work began with measurements of excess noise characteristics of four $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ (with x from 0.0 to 0.15) p-i-n diodes with 110-116 nm avalanche layer thickness [7]. Using a 543 nm wavelength laser as excitation source, which did not achieve pure electron injection, the best data corresponded to an effective ionization coefficient ratio, k_{eff}, of 0.1. Recently the excess noise measurements were improved in [8], which used a 420 nm wavelength excitation source to achieve pure electron and pure hole injection for p–i-n and n-i-p diodes, respectively. Data of $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ p-i-n diodes from [8] corresponded to k_{eff} as low as 0.05-0.08. Both works found electron injection to be preferable for achieving the lowest possible excess noise characteristics, hence electrons have higher ionization coefficient than holes.

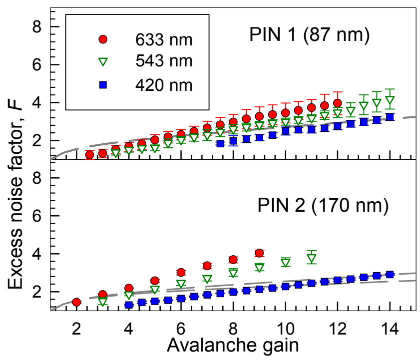

Fig. 2. Excess noise factor versus avalanche gain characteristics measured from two $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ p-i-n didoes (87 and 170 nm avalanche layer thickness), using different excitation wavelengths (symbols) [8]. Fittings (grey lines) indicate the data correspond to k_{eff} of 0.1 (top) and 0.05-0.08 (bottom).

IV. Temperature Dependence

Typical industrial range of operating temperatures for semiconductor devices is from -40 to +85 °C. As the operating temperature increases, the APD's gain usually decreases (with InAs and HgCdTe being the notable exceptions) and the avalanche breakdown voltage, V_{bd}, increases. To maintain the avalanche gain, the system must either adjusting the applied bias or use temperature control. It is therefore advantageous to have APDs with weak temperature dependence of avalanche gain and V_{bd}.

Our experimental data on the temperature dependence of avalanche gain and V_{bd} of $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ APDs cover from -193 to +80 °C [9, 10]. In [9], V_{bd} of four $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ (x = 0 to 0.15) p-i-n diodes were extracted from avalanche gain versus reverse bias characteristics as function of temperature (from -193 °C, or 80 K, to room temperature). These V_{bd} in turn yielded temperature coefficient of breakdown voltage, $C_{bd} = \Delta V_{bd}/\Delta T$. The C_{bd} values obtained from the $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ (x = 0 to 0.15) p-i-n diodes are very low, when compared to reported values for other avalanche materials, as shown in Fig. 3.

More recent work [10], which focused on $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ p-i-n diodes, confirmed that the low C_{bd} values is also valid between room temperature and 80 °C. Hence $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ exhibit very weak temperature dependence of avalanche gain and breakdown voltage.

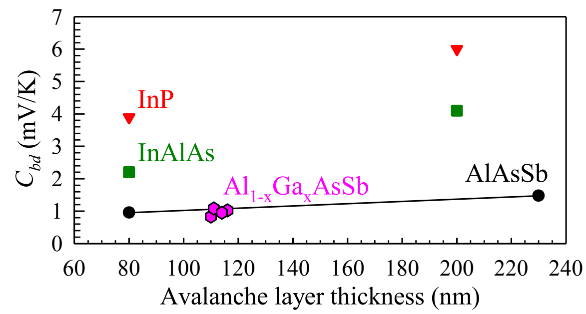

Fig. 3. Temperature coefficient of avalanche breakdown voltage versus avalache layer thickness of $Al_{1-x}Ga_xAs_{0.56}Sb_{0.44}$ (x = 0 to 0.15) p-i-n didoes [9], compared to other avalanche materials (InP and InAlAs).

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