Room-temperature bandwidth of 2-µm AllInAsSb avalanche photodiodes

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Abstract: We investigate the room-temperature bandwidth performance of AllInAsSb avalanche photodiodes under 2-µm illumination. Parameter characterization denotes RC-limited performance. While measurements indicate a maximum gain-bandwidth product of 44 GHz for a 60-µm-diameter device, we scale this performance to smaller device sizes based on the RC response. For a 15-µm-diameter device, we predict a maximum gain-bandwidth product of approximately 144 GHz based on the reported measurements.

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1. Introduction

Avalanche photodiodes (APDs) have been widely deployed in imaging and Light Detection and Ranging (LIDAR) applications due to their high optical sensitivity [1]. This sensitivity arises from the process of impact ionization within the devices, which results in an intrinsic multiplication of the photogenerated carriers. The stochastic nature of impact ionization gives rise to a noise mechanism in APDs, quantified by the excess noise factor [2]. This is a prominent factor in the detector shot noise and is therefore an essential contributor to the overall signal-to-noise ratio of an APD. The sensitivity of an APD-based receiver is dependent upon the mitigation of this noise, as lower excess noise allows for the direct increase of sensitivity via an increase in gain [3]. The reduction of APD noise is also directly linked to increased operating bandwidth [4], further accentuating the importance of low-noise APDs.

Although bandwidth requirements for imaging and LIDAR applications are much lower than those for communications systems, these bandwidths, as well as the sensitivities afforded by APDs, are essential for high-resolution, long-distance detection of moving objects [5]. While many infrared wavelengths have been employed for LIDAR applications, recently, the 2-µm band has received increased interest due to its improved eye safety [6] and use for CO2 sensing [7]. Non-avalanching 2-µm photodiodes have been reported in several materials systems with GHz bandwidths [8–10]. However, the use of APDs for this wavelength presents additional challenges, as the commonly used materials systems (HgCdTe and InAs) often require significant cooling to operate. While room-temperature bandwidth measurements of InAs APDs do exist, they are measured at shorter wavelengths [3]. To our knowledge, there are no reported room-temperature APD bandwidth measurements at 2 µm.

AllInAsSb digital-alloy APDs have recently demonstrated wide bandgap tunability [11], high gain [12], high temperature stability [13], and very low excess noise [14–18]. As a result, AllInAsSb APDs with optimized RC and transit-time characteristics could offer a high-performance bandwidth and related gain-bandwidth product.

The use of AllInAsSb in a separate absorption, charge and multiplication (SACM) APD for 2-µm light was previously demonstrated with extremely low noise and superior dark current performance [18]. Here we report the room-temperature bandwidth performance of these devices at 2 µm and investigate potential improvements through device scaling.
2. Experimental methods

The details regarding the growth of the AlInAsSb digital alloy are provided elsewhere [11]. Details relating to the fabrication and characterization of the aforementioned 2-µm AlInAsSb SACM APD, including dark current, gain, efficiency, and noise performance, are also reported elsewhere [18]. For reference, the epitaxial layer structure of the SACM APD is shown in Fig. 1.

![Fig. 1. The epitaxial layer structure of the SACM APD.](image)

For measurements, a 60-µm diameter APD was contacted with a ground-signal-ground (GSG) probe. A Keithley 2400 source meter was used to bias the APD, which was connected via a bias tee to an Agilent E4440A spectrum analyzer to measure the RF output power. A temperature-stabilized 2-µm laser was coupled to a LiNbO₃ Mach-Zehnder modulator and focused onto the device using a lensed fiber. A Keysight N5227A vector network analyzer was used to measure the device $S_{11}$ parameters as well as the $S_{12}$ parameters of the measurement setup, in order to isolate the device response from that of the test setup itself.

3. Results

3.1. Bandwidth and parameter characterization

The room-temperature RF output power of the APD was measured at 100-MHz intervals and analyzed with a best-fit curve in order to determine the 3-dB bandwidth. Figure 2 shows these measurements at high gain values. At the punch-through voltage (-23 V), the 3-dB bandwidth was limited to approximately 1 GHz but improved to 1.44 GHz with additional reverse bias, likely due to increased field within the absorber, allowing electrons to more easily drift into the multiplication region. At the maximum measured gain ($M \approx 37.6$), the 3-dB bandwidth was reduced to 1.17 GHz as a result of the increased avalanche buildup time. The measurements at this point resulted in a maximum gain-bandwidth product of 44 GHz. Figure 2 illustrates the 3-dB bandwidth measurements and best-fit curves for the highest 4 measured gain values, as indicated.

Input impedance was investigated within the operating range of the device, above the punch-through voltage. As shown in Fig. 3, $S_{11}$ parameters measured from 10 MHz to 3.5 GHz were fit using a standard circuit model, revealing the constant series resistance ($R_S$) to be 3255 $\Omega$. 

Measurements at different gain values only slightly changed the junction capacitance ($C_J$) and stray capacitance ($C_S$), which were fit to 31.4 fF and 150 fF, respectively, at 40 V reverse bias. Subsequent transmission line measurements, shown in Fig. 4, revealed the primary contributor to the high $R_S$ value was the top P contact, largely due to high sheet resistance, which could be caused by GaSb oxidation at the surface. High-quality ohmic contacts have been reported on P-type GaSb [19], suggesting that this resistance could be reduced with improved material quality or fabrication techniques.

3.2. Performance scalability

It is well understood that for simple photodiodes, bandwidth performance is limited by RC and transit-time effects. However, for APDs with non-negligible gain, a third component, the avalanche buildup time, must be considered. In this work, we follow the simple model given by Ref. [20] for accommodating these effects. Here, for simplicity, we will assume the carrier saturation velocity ($v$) is $1 \times 10^7$ cm/s, which has been observed in other III-V materials and used to approximate the transit time [21,22]. The overall transit time ($\tau_t$) is then given by

$$\tau_t = \frac{2w_d}{v} + \tau_m$$  \hspace{1cm} (1)

where $w_d$ is the width of the absorption region of the device and $\tau_m$ is the avalanche buildup time. For this device, we will take the absorber as well as the grading and charge layers as $w_d$ since the carriers must transit this region in addition to the absorber before entering the high-field region. $\tau_m$ is given by

$$\tau_m = \frac{Mkw_m}{v} + \frac{w_m}{v}$$  \hspace{1cm} (2)

where $M$ is the gain, $k$ is the ratio of the impact ionization coefficients (0.01 in this case) [18], and $w_m$ is the width of the multiplication region [20]. For the gain values investigated in this work, the calculated transit time limited bandwidth, including the avalanche buildup time, ranges from 5.15 to 4.9 GHz.
Fig. 3. The circuit model (a) used for fitting the measured $S_{11}$ parameters from 10 MHz to 3.5 GHz. Measured and fit $S_{11}$ magnitude and phase parameters are shown in (b) and (c), respectively. Measured values are shown in blue, and simulated values are shown in red.

Fig. 4. Transmission line measurements of the N (black) and P (red) contacts.
The other factor that contributes to the bandwidth is the RC time constant, which for a PIN photodiode, based on the model in Fig. 3(a), neglecting $R_J$, is given by

$$f_{RC} = \frac{1}{2\pi RC} = \frac{1}{2\pi [R_L C_S + (R_S + R_L) C_J]}$$

where $C_S$ and $C_J$ are the stray and junction capacitances, and $R_S$ and $R_L$ are the series and load resistances of the device, respectively. For an SACM APD, this relation still holds, as above the punch-through voltage when the low-background absorber has depleted, the device is fully depleted between the P and N contact regions. For the design shown in Fig. 1, only $R_S$ and the device area can be easily modified without altering the epitaxial design itself. Since it is established that $R_S$ could be reduced with improved material quality or fabrication techniques, we investigate performance improvements which result from reducing $C_J$ via the device area.

**Fig. 5.** (a) The measured 3-dB bandwidth of a 60-µm-diameter device and the calculated 3-dB bandwidths of smaller diameter devices. (b) The measured gain-bandwidth product of a 60-µm-diameter device and the calculated gain-bandwidth products of smaller diameter devices.
We begin by calculating the RC bandwidth by Eq. (1) using the fitted values from the 60-µm device $S_{11}$ measurements above. Subsequently, the 3-dB bandwidth can be calculated by

$$f_{3\text{dB}} \approx \left( \frac{1}{f_{RC}^2} + \frac{1}{f_t^2} \right)^{-\frac{1}{2}}$$

where $f_{RC}$ and $f_t$ are the RC bandwidth and the overall transit-time bandwidth, respectively.

Figure 5(a) shows the measured 3-dB bandwidth of a 60-µm-diameter device as a function of gain and how these results improve by reducing the device diameter and thereby reducing $C_J$. The calculated 3-dB bandwidth of a 60-µm device based on the fit parameters is also included. For a 15-µm device, the calculated 3-dB bandwidth is approximately 4.9 GHz at low gain and reduces to 3.8 GHz at the maximum gain. Similarly, Fig. 5(b) shows the measured gain-bandwidth product of a 60-µm-diameter device as a function of gain as well as the calculated performance of smaller diameter devices. The maximum calculated gain-bandwidth product for a 15-µm-diameter device is approximately 144 GHz.

4. Conclusion

While bandwidth is less of a concern for LIDAR and imaging than in telecom applications, it is nevertheless an important figure of merit in high-speed, high-resolution imaging. With the increased interest in the use of 2-µm light for these applications, bandwidth performance must be well characterized. APDs in imaging applications often require thick absorbing regions in order to provide improved efficiency, which necessarily increases the carrier transit time and reduces the bandwidth for normal-incidence devices.

We have demonstrated a maximum measured 2-µm gain-bandwidth product of 44 GHz and a calculated gain-bandwidth product of approximately 144 GHz for smaller device sizes. Further reduction of device series resistance, as well as optimization of contact pads could provide additional bandwidth improvement. Due to their extremely low noise, excellent dark current and GHz bandwidth performance, these AlInAsSb APDs provide an ideal solution for 2-µm imaging and LIDAR applications.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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