Temperature dependence of avalanche breakdown of AlGaAsSb and AlInAsSb avalanche photodiodes


Abstract—Digital alloy Al$_{0.85}$Ga$_{0.15}$As$_{0.56}$Sb$_{0.44}$, random alloy Al$_{0.85}$Ga$_{0.15}$As$_{0.56}$Sb$_{0.44}$, and random alloy Al$_{0.75}$In$_{0.25}$As$_{0.74}$Sb$_{0.26}$ are promising candidates for the multiplication regions of avalanche photodiodes (APDs) due to their low excess noise, which is comparable to that of Si APDs. The temperature dependence of avalanche breakdown in these materials has been investigated by measuring the multiplication gain. A weak temperature dependence of the breakdown voltage is observed, which is desirable to reduce the complexity of temperature or reverse bias control circuits in the optical receiver. Calculations of the alloy disorder potentials and alloy scattering rates indicate that the temperature dependence of the avalanche breakdown in these quaternary alloys is attributable to the dominant of large mass variations and high alloy scattering over phonon scattering. Impact ionization can also be impacted by the temperature dependence of the bandgap energy which affects the ionization threshold energy. Therefore, the temperature dependence of the bandgap energy has been investigated by temperature-dependent photoluminescence and external quantum efficiency measurements to further explain the temperature dependent breakdown characteristics of these materials.

Index Terms—Avalanche breakdown, bandgap energy, AlGaAsSb, AlInAsSb temperature dependence, digital alloy, random alloy.

I. INTRODUCTION

Avalanche photodiodes (APDs) are beneficial for detecting weak optical signals, leading to their utilization in a wide range of commercial, research, and military applications [1, 2]. Their internal multiplication gain results from the stochastic impact ionization process, and higher receiver sensitivity can be achieved relative to unity-gain photodiodes. Typically, in the impact ionization process, the carriers obtain the ionization threshold energy by accelerating in a high electric field multiplication region [3], and loss of energy occurs primarily through scattering, with phonon scattering being dominant. Phonon scattering exhibits strong positive temperature dependence. This results in significant variation of the gain with temperature; higher reverse bias is required to maintain the same gain at higher temperature. In practice, in order to maintain a stable gain, an active variable bias circuit or a thermoelectric cooler is required to control either the applied reverse bias or the operating temperature, increasing the cost and the system complexity [4]. The simplest and most straightforward way to simplify the bias or temperature control circuits is to choose a multiplication material with weak temperature dependence of avalanche breakdown. The temperature sensitivity is characterized by the temperature coefficient of breakdown voltage [5], which is expressed as

$$C_{bd} = \frac{\Delta V_{bd}}{\Delta T},$$

where $\Delta V_{bd}$ is the change of the breakdown voltage, and $\Delta T$ is the change of the temperature. The temperature coefficient of breakdown voltage is determined by not only the material but also the multiplication layer thickness. As the multiplication layer thickness increases, $C_{bd}$ increases due to increased phonon scattering [6].

The choice of the multiplication layer material is determined by various factors including dark current, excess noise, and the temperature coefficient of the breakdown voltage. The excess noise is typically included as a multiplicative term, referred to as the excess noise factor, $F(M)$, in the shot noise current, $I_{shot}$, which is
which can be expressed as [7]

\[ i_{\text{bias}} = 2q \left( I_{\text{photo}} + I_{\text{dark}} \right) M^2 F(M) \Delta f, \]

where \( I_{\text{photo}} \) and \( I_{\text{dark}} \) are the photocurrent and dark current, respectively, \( M \) is the average value of the gain, and \( \Delta f \) is the bandwidth. In the local field model for pure electron injection [7],

\[ F(M) = kM + (1-k) \left( 2 - \frac{1}{M} \right), \]

where \( k \) is the ratio of the hole impact ionization coefficient to the electron impact ionization coefficient. A lower \( k \) value is desirable to reduce the excess noise, leading to higher receiver sensitivity and higher gain-bandwidth product. Recently, Al_{1-x}As_{x}Sb_{1-y} and Al_{1-x}Ga_{x}Sb_{1-y} material systems [2] have been reported \( k \) values comparable to that of Si \((k \sim 0.01)\) [7, 8] and lower than that of In_{0.52}Al_{0.48}As \((k \sim 0.2)\) [9, 10] or InP \((k \sim 0.45)\) [11]. These two Sb-based material systems are promising candidates for the multiplication regions in the separate absorption, charge, and multiplication (SACM) APDs. Furthermore, thick digital alloy (DA) Al_{1-x}In_{x}Sb_{1-y} lattice-matched to GaSb with \( x = 0.6, 0.7, 0.8, 12-14 \) and thin random alloy (RA) Al_{1-x}Ga_{x}Sb_{1-y} lattice-matched to InP with \( x = 1, 0.95, 0.9, 0.85 \) [15, 16] have shown a weak temperature dependence of avalanche breakdown. Recently, we have reported low \( k \) values for thick random alloy Al_{0.7}In_{0.2}As_{0.76}Sb_{0.24} APDs [17], thick digital alloy Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44} APDs [18], and thick random alloy Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44} [19] APDs lattice-matched to InP. It follows that it is useful to determine the temperature characteristics of these material systems.

In this work, the avalanche breakdown with temperature variation was studied for digital alloy Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}, random alloy Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44} (hereafter Al_{0.85}GaAsSb), and random alloy Al_{0.7}In_{0.2}As_{0.76}Sb_{0.24} (hereafter Al_{0.7}InAsSb) \( p^+\)-\( i\)-\( n^+ \) APDs. An explanation for the weak temperature dependence of avalanche breakdown is provided by calculating alloy disorder potentials and alloy scattering rates. In addition, the variation of the bandgap with temperature was investigated with photoluminescence and quantum efficiency measurements.

### II. Epitaxial Crystal Growth and Device Fabrication

All three wafers were grown as \( p^+\)-\( i\)-\( n^+ \) structures by molecular beam epitaxy. One of the Al_{0.85}GaAsSb wafers lattice-matched to InP was grown as a digital alloy [18] and the other as a random alloy [19]. The Al_{0.7}InAsSb wafer lattice-matched to InP was grown as a random alloy [17]. The layer structures are shown in Table I, and the multiplication layer thickness were taken from capacitance-voltage (C-V) measurements [20]. Be and Si were used as p-type and n-type dopants, respectively.

Circular mesa structures were defined by photolithography and formed by the chemical etching with a solution of citric and phosphoric acid [21]. The top and bottom Ti and Au contacts were then deposited by electron-beam evaporation. Finally, the sidewalls were passivated by SU-8 to suppress the surface dark current.

<table>
<thead>
<tr>
<th>Types</th>
<th>Material</th>
<th>Thickness (nm)</th>
<th>Doping (cm(^-3))</th>
</tr>
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<tbody>
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<td>Digital alloy</td>
<td>Al_{0.85}GaAsSb</td>
<td>300</td>
<td>( p^+ = 1 \times 10^{19} )</td>
</tr>
<tr>
<td>Al_{0.85}GaAsSb</td>
<td>300</td>
<td>( p^+ = 2 \times 10^{18} )</td>
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<td></td>
<td>890</td>
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<tr>
<td></td>
<td>100</td>
<td>( n^+ = 2 \times 10^{18} )</td>
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<tr>
<td></td>
<td>400</td>
<td>( n^+ = 1 \times 10^{19} )</td>
<td></td>
</tr>
<tr>
<td>Random alloy</td>
<td>Al_{0.7}InAsSb</td>
<td>300</td>
<td>( p^+ = 2 \times 10^{18} )</td>
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<td></td>
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<tr>
<td></td>
<td>500</td>
<td>( n^+ = 1 \times 10^{19} )</td>
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</table>

### III. Temperature-Dependent Avalanche Breakdown

APDs were placed in a nitrogen-cooled cryogenic chamber, and a temperature controller was used to monitor the temperature. The current-voltage (I-V) characteristics of 150-um-diameter APDs were measured under dark and illuminated conditions. A 520-nm fiber-coupled laser source was used to illuminate the device. The gain, \( G \), was calculated from the photocurrent, and the breakdown voltage can be determined by the extrapolation of the inverse gain, 1/\( G \), to zero. This 1/\( G \) extrapolation method has been utilized in various Al_{1-x}Ga_{x}Sb_{1-y} and Al_{1-x}In_{x}As_{1-y} samples, and a good linear fitting of 1/\( G \) vs. \( I \) has been obtained [12-16]. Due to the absence of temperature-dependent impact ionization coefficients for Al_{0.85}GaAsSb and Al_{0.7}InAsSb, the breakdown voltage cannot be directly determined by the simulation of multiplication gain for these three samples [4]. Finally, the temperature coefficient of breakdown voltage, \( C_{bd} \), is the slope of the linear fitting to the breakdown voltages under different temperatures.

Figure 1 shows (a) the gain versus voltage, (b) the inverse gain curves, and (c) the dark current in the range of 78 K to 360 K for DA Al_{0.85}GaAsSb APDs. Figure 2 shows similar curves for RA Al_{0.85}GaAsSb APDs in the temperature range of 200 K to 340 K. The measurements on RA Al_{0.7}InAsSb APDs in the temperature range of 200 K to 320 K are shown in Fig. 3. Based on the linear regression approach, the fitting curves of breakdown voltages under different temperatures are calculated in Fig. 4, and the \( C_{bd} \) is determined to be (4.22 ± 0.08) mV/K, (5.92 ± 0.36) mV/K, and (5.91 ± 0.37) mV/K for DA Al_{0.85}GaAsSb, RA Al_{0.85}GaAsSb, and RA Al_{0.7}InAsSb APDs. Values of \( C_{bd} \) for these three materials, commercially available materials (including InP, InAlAs, Si [5, 6]), and recently reported Sb-based materials [4, 12-16] are shown in Fig. 5. The temperature coefficient of breakdown voltage of these three
materials are significantly lower than InP, InAlAs, or Si [5, 6] with the same multiplication layer thickness.

Fig. 1. (a) Measured gain curves, (b) inverse gain (symbols) and linear fitting (solid lines) under 520-nm illumination, and (c) dark current curves for 150-µm-diameter p–i–n’ DA Al_{0.85}GaAsSb APDs from 78 K to 360 K.

Fig. 2. (a) Measured gain curves, (b) inverse gain (symbols) and linear fitting (solid lines) under 520-nm illumination, and (c) dark current curves for 150-µm-diameter p–i–n’ RA Al_{0.85}GaAsSb APDs from 200 K to 340 K.
IV. DISCUSSION

A. Role of Alloy Scattering in Sb-based Quaternary Alloys

Previously, it has been observed that ternary alloys have lower $C_{bd}$ compared to binary compounds [22]. The low $C_{bd}$ of ternary alloys was attributed to the dominance of alloy scattering over phonon scattering. In a random alloy, for example a ternary alloy, the constituent atoms are distributed in a random manner which leads to fluctuations in the crystal potential. This fluctuating potential results in an effective scattering process, referred to as alloy scattering, which impacts the movement of electrons through the crystal [23]. In contrast, the digital alloys are short-period superlattices that consist of binary alloy layers stacked alternately in a periodic manner. Due to the small thickness of these binary layers, there is interface roughness, leading to fluctuations of the crystal...
potential at the interfaces. This paper has demonstrated that Sb-based quaternary alloys exhibit even lower $C_{bd}$ in comparison to both ternary and binary alloys. Thus, it appears that alloy scattering also plays a significant role in the temperature dependence of the breakdown voltage for these materials. To understand the significance of this scattering mechanism in these materials, their alloy disorder potentials and alloy scattering rates were studied.

The alloy scattering rate for a quaternary alloy is given by [24]

$$\frac{1}{\tau} = \frac{3\pi}{8\sqrt{2}} \left( \frac{m^*}{h^4} \right)^{3/2} \gamma(E) \frac{d\nu}{dE} \Omega \left| \Delta U_0 (x, y) \right|^2 S$$

with

$$\left| \Delta U_0 (x, y) \right|^2 = x(1-x)2\left[ \Delta U_{AbD} \right]^2 + x(1-2x)(1-y)\left[ \Delta U_{AbC} \right]^2 + x^2y(1-y)\left[ \Delta U_{Bcd} \right]^2 + (1-x)^2y(1-y)\left[ \Delta U_{AbD} \right]^2,$$

where the $\Delta U_0$ is the alloy disorder potential of the quaternary alloy. The $\Delta U^0$ on the right hand side of the equation represent the disorder potential of ternary alloys. For example, the potential $\Delta U_{AbD}$ is for a ternary alloy with composition $A_{1-x}B_{x}D$, and the potential $\Delta U_{Bcd}$ is for $B_{x}C_{1-x}D$. The alloy disorder potential arises due to the potential fluctuations created by the different nuclei sizes of the constituent atoms. In (4), $m^*$ is the carrier effective mass, $\Omega$ is the primitive cell volume, and $\gamma(E) = E(1+\sigma E)$ describes the non-parabolic nature of the electronic band structure with $E$ representing the carrier energy and $\sigma$ describing the non-parabolicity. The ordering of atoms is described by the factor $S$. For completely random systems $S = 1$, and $S = 0$ for perfectly ordered systems. In our simulations, we assume $S = 1$. For a ternary alloy $A_{1-x}B_xC$, the disorder potential can be calculated by

$$\Delta U = \frac{bZ}{4\pi\varepsilon_0} \left( \frac{1}{r_A} - \frac{1}{r_B} \right) \exp(-k_r R),$$

where $b$ accounts for the fact that the Thomas Fermi theory overestimates the screening in the semiconductor and has a value of 1.5 for most zinc blende binary semiconductors. $Z$ is the valence number of $A$ and $B$, $\varepsilon_0$ is the vacuum permittivity, and the covalent radii of the atoms $A$, $B$ and $C$ are given by $r_A$, $r_B$, and $r_C$, respectively. $k_r = \sqrt{4k_F / \pi a}$ is the Thomas Fermi screening wave number in a three-dimensional system, where $a$ is the Bohr radius, and $k_F = (3\pi^2N_{val})^{1/3}$ is the Fermi wave number in a three-dimensional system. The valence electron density $N_{val} = 32/a^3$, and the bond length of this ternary alloy $R = 0.5\left[ (x+y) + (1-x) \right]$. In (5), it is seen that the alloy disorder potential primarily depends on the difference in covalent radii of the constituent atoms and their valence number. Figure 6 shows the comparison of $C_{bd}$ vs. $\Delta U^2$ for various III-V binary, ternary, and quaternary alloys. The ternary alloy potentials are scaled by the factor $\nu(1-x)$, where $\nu$ is the mole fraction for atom $B$ in $AB:C_{1-x}$, to make a valid comparison with quaternary alloy potentials [22]. The $C_{bd}$ values for the binary and ternary alloys are obtained from the literature [4, 22], and they are for the APDs with 1-µm multiplication layer thickness. A larger radius difference leads to a higher alloy disorder potential. For example, InAlAs has a larger potential in comparison to AlGaAs because there is a large difference in the Al and In covalent radii whereas the Al and Ga covalent radii are similar. Also, alloys with different group V elements have a higher disorder potential in comparison to alloys with varying group III elements due to the larger valence number of group V elements.

We computed the alloy disorder potentials for the Sb-based quaternary alloys by using (5). $\Delta U = 0.46$ eV for RA Al$_{0.79}$InSb and $\Delta U = 0.45$ eV for RA Al$_{0.79}$InAsSb were obtained. The $\Delta U^2$ of the Sb-based ternary and quaternary alloys are significantly larger than other III-V alloys shown in Fig. 6. Consequently, the breakdown voltage of the Sb-based alloys has the weakest temperature dependence due to the large difference in the covalent radii of As and Sb atoms, which are also group V elements. The resulting higher disorder potential of these alloys leads to an increased alloy scattering rate, given by (4), which then dominates over the phonon scattering leading to a weaker temperature dependence of the avalanche breakdown. The underlying factor for the temperature dependence of the avalanche breakdown is phonon scattering which can be altered by the temperature-dependent phonon population. A more dominant scattering mechanism, like alloy scattering, suppresses the phonon scattering mechanism which ultimately reduces the temperature dependence.

To further highlight the role of Sb atoms in the quaternary alloys, we plotted the alloy scattering rates of RA InAlAs, RA Al$_{0.79}$InSb, RA Al$_{0.85}$GaAsSb and RA AlAsSb in Fig. 7. The quaternary alloys containing Sb demonstrate much higher scattering rates in comparison to that of the ternary InAlAs. The higher scattering rates of the quaternary alloys arise from their higher alloy disorder potentials, and potentially lower electron-phonon coupling. This is consistent with experimental observation that InAlAs has a stronger temperature dependence of avalanche breakdown than the quaternary alloys do. In the
simulation, we used effective masses of 0.072m₀, 0.111m₀, 0.152m₀, and 0.0982m₀ for InAlAs, Al₀.70InAsSb, Al₀.85GaAsSb, and AlAsSb, respectively. The corresponding bandgaps for these four materials are 1.4 eV, 1.73 eV, 1.59 eV and 1.65 eV. The lattice constant of InP (5.9117 Å), which is the substrate for all three alloys, is used. The DA scattering rates cannot be included here since their corresponding value of S is unknown. The values can be extracted by carrying out Monte Carlo simulations with alloy scattering for these alloys and calibrating with experimental results.

The breakdown voltage temperature dependence is primarily due to the scattering processes, like phonon and alloy scattering, as mentioned earlier. Since the bandgap stability under different temperatures has some impact on the temperature dependence of avalanche breakdown, and it is instructive to investigate the bandgap stability of Sb-based quaternary materials as well.

Temperature-dependent photoluminescence (PL) [25] measurement was used to investigate the temperature dependence of the bandgap energy for DA Al₀.5In₀.5AsSb₁-y lattice-matched to GaSb [26], RA Al₀.70InAsSb lattice-matched to InP [17], and DA Al₀.85GaAsSb lattice-matched to InP [18]. The measured bandgap energy can be fitted by the Varshni equation [27],

$$E(T) = E_0 - \frac{\alpha T^2}{T + \beta}$$

where $E(T)$ is the energy gap at temperature $T$, $E_0$ is the energy gap at 0 K, and $\alpha$ and $\beta$ are constants.

As shown in Fig. 8(a) and 8(b), the bandgap of DA Al₀.5In₀.5AsSb₁-y and RA Al₀.70InAsSb was determined in the temperature range of 95 K – 295 K and 160 K – 300 K, respectively. The data points were then fitted by the Varshni equation [27]. The temperature-dependent bandgap curves of these two Sb-based quaternary materials were compared with binary materials (including AlAs, AISb, InAs, InSb [28]); the Sb-based materials exhibit smaller shifts with temperature. Furthermore, the results show that both digital alloy growth and random alloy growth can provide the weak temperature dependence of bandgap for Al₁In₁-xAsSb₁-y. Therefore, the digital alloy growth itself cannot explain the bandgap stability. Figure 8(c) shows the temperature-dependent bandgap for DA Al₀.85GaAsSb in the temperature range of 160 K to 300 K, and the data points were fitted by the Varshni equation [27]. The same conclusion that the temperature dependence of the bandgap of the quaternary material is weaker than binary materials (including AlAs, AISb, GaAs, GaSb [28]) can be drawn for DA Al₀.85GaAsSb.

Temperature-dependent external quantum efficiency (EQE) measurement [21] was carried out to investigate spectrum cutoff under different temperatures for DA Al₀.7In₀.3AsSb₁-y lattice-matched to GaSb [29]. As shown in Fig. 9, external quantum efficiency measurements were carried out in the temperature range of 258.15 K to 298.15 K for DA Al₀.7In₀.3AsSb₁-y. Based on shifts in the response near cutoff, the bandgap variation with temperature was determined to be 0.29 meV/K, which is consistent with the PL measurements. In summary, both temperature-dependent PL measurements and EQE measurements demonstrate weak variation of the bandgap with temperature for Al₁In₁-xAsSb₁-y and Al₁Ga₁-xAsSb₁-y material systems, irrespective of growth method. The temperature dependence of the material bandgap is primarily attributed to electron-phonon interactions [30] that broaden the material energy states and result in the creation of energy states within the bandgap. The effect of thermal expansion on the temperature dependence is very small for covalent compounds [31]. The weak temperature dependence of bandgap for these
Sb-based quaternary alloys most likely arises from the weak electron-phonon coupling in these materials. The weak coupling results in a small broadening of the energy states and hence fewer energy levels created within the bandgap. It is possible that such weak temperature dependence of the material bandgap will somewhat lower the $C_{bd}$ primarily as a higher order effect. On the other hand, a stronger electron-phonon coupling will most likely cause some increase in $C_{bd}$. Further investigations are needed to be carried out to determine the exact contribution of electron-phonon interactions on $C_{bd}$.

Fig. 8. Temperature-dependent photoluminescence peaks (points) and the Varshni fitting curves (solid lines) for (a) DA Al$_{0.45}$In$_{0.55}$Sb on GaSb, (b) RA Al$_{0.70}$In$_{0.30}$Sb on InP, and (c) DA Al$_{0.50}$GaAsSb lattice-matched to InP. The dash lines represent the Varshni fitting curves for the binary materials including AlAs, AlSb, InAs, InSb, GaAs, GaSb [28], and the $E_0$ of binary materials has been modified according for a better comparison with the investigated quaternary materials.

Fig. 9. Temperature-dependent external quantum efficiency for DA Al$_{0.50}$In$_{0.50}$Sb$_{0.45}$ lattice-matched to GaSb.

V. CONCLUSION

Temperature dependence of avalanche breakdown has been investigated for digital alloy Al$_{0.85}$Ga$_{0.15}$As$_{0.50}$Sb$_{0.44}$, random alloy Al$_{0.85}$Ga$_{0.15}$As$_{0.50}$Sb$_{0.44}$, and random alloy Al$_{0.79}$In$_{0.21}$As$_{0.71}$Sb$_{0.26}$. We observe weak dependence of the avalanche breakdown voltage on temperature for the Sb-based quaternary materials. Temperature-dependent photoluminescence and external quantum efficiency measurements reveal weak temperature dependence of the bandgap. Modeling supports that these quaternary alloys have high alloy scattering rates dominating over phonon scattering mechanisms that reduce the temperature dependence of the avalanche breakdown. This weak temperature dependence has the benefit of simplifying the temperature or reverse bias control circuits while maintaining a constant multiplication.
gain in an optical receiver.

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