High temperature and wavelength dependence of avalanche gain of AlAsSb avalanche photodiodes

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The evolution of the dark currents and breakdown at elevated temperatures of up to 450 K are studied using thin AlAsSb avalanche regions. While the dark currents increase rapidly as the temperature is increased, the avalanche gain is shown to only have a weak temperature dependence. Temperature coefficients of breakdown voltage of 0.93 and 1.93 mV/K were obtained from the diodes of 80 and 230 nm avalanche regions (*i*-regions), respectively. These values are significantly lower than for other available avalanche materials at these temperatures. The wavelength dependence of multiplication characteristics of AlAsSb *p-i-n* diodes has also been investigated, and it was found that the ionization coefficients for electrons and holes are comparable within the electric field and wavelength ranges measured. © 2011 Optical Society of America

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Single photon avalanche photodiodes (SPADs) are commonly used in quantum key distribution systems for secure communications [1]. SPADs exploit the processes of impact ionization to provide gain, allowing their sensitivity to be greatly enhanced. However, it is well known that this process is strongly temperature dependent. In most wide bandgap semiconductors, such as Si, GaAs, and InP, this temperature dependence results in a decrease in the multiplication gain as the temperature increases, leading to an increase of the breakdown voltage, V_{bd}. The temperature dependence is described by the variation in the breakdown voltage by $C_{bd} = \Delta V_{bd}/\Delta T$, where ΔV_{bd} is the change in breakdown voltage and ΔT is the temperature change. To overcome this problem, SPADs are operated in conjunction with a biasing circuit or a thermoelectric cooler to maintain a constant gain and give reproducible performance. However, this adds additional cost and complexity to the final system. Moreover, recently Lydersen *et al.* [2] demonstrated that it is possible to exploit the temperature dependence of gain to prevent commercial SPADs from operating in the Geiger mode. This was done by using high optical power to increase the breakdown voltage of the SPADs.

The temperature dependence has been shown to be reduced in various semiconductors when the avalanche region width, w, is reduced. This effect has been observed in Si, where C_{bd} has been shown to decrease from 20 to 1.53 mV/K as w decreases from 800 to 100 nm [3], and a change from 28 to 0.56 mV/K has been observed in GaAs as w decreases from 1000 to 25 nm [4]. This reduction in C_{bd} with decreasing width can be attributed to a reduced phonon scattering at high electric fields. A reduced avalanche width also helps to lower the excess avalanche noise [5] and increase the gain–bandwidth product due to a reduced carrier transit time [6]. However, a thin avalanche region often leads to a concomitant rise in the band-to-band tunneling current, placing a reduced limit on the practical avalanche width [7].

It has recently been shown that by using the wider bandgap material $\mathrm{AlAs_{0.56}Sb_{0.44}}$ (AlAsSb) lattice matched to InP, reduced avalanche widths can also be realized without causing an increase in the band-to-band tunneling [8]. A reduced C_{bd} compared to other materials with comparable avalanche widths was also reported here. However, this study only covered the performance at low temperatures. In a practical application an SPAD or avalanche photodiode (APD) handling a high photocurrent would operate at higher temperatures due to self-heating effects. Therefore, the temperature dependence of the breakdown at elevated temperatures is a more important parameter to understand.

The intrinsic absorption and impact ionization properties of this material are also unknown and require a more in-depth study to help optimize future device design. In this Letter we evaluate the absorption properties of AlAsSb as a function of wavelength and also investigate the temperature dependence of breakdown at high temperatures in AlAsSb APDs.

Two wafers were grown by molecular beam epitaxy on semi-insulating InP substrates. Both wafers consist of a 1 μm InGaAs etch stop layer followed by a 50 nm thick AlAsSb layer (where were both n doped with Si to 5×10^{18} and 2×10^{18} cm^3, respectively). The intrinsic multiplication width consists of an undoped AlAsSb layer, which was 80 nm thick (PIN 1) or 230 nm thick (PIN 2), where the thicknesses were determined from measurements and modeling of the voltage-dependent capacitance of the devices. The wafers had a 400 nm thick AlAsSb p-cladding, followed by a 50 nm InGaAs cap (where each was doped with Be to 2×10^{18} and 5×10^{18}, respectively). The wafers were fabricated into circular mesa diodes with varying sized radii.

For current–voltage (I–V) and photocurrent measurements the devices were packaged onto TO-5 headers, while for the multiplication measurements devices were directly probed on chip. To isolate the influence of dark current on the photocurrent and multiplication

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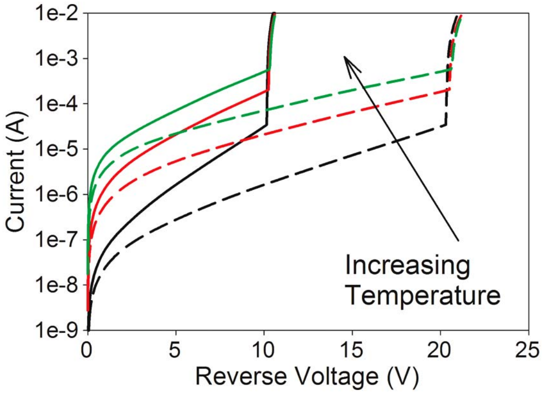

Fig. 1. (Color online) Measured *I*–*V* characteristic for PIN 1 (solid curve) and PIN 2 (dashed curve) at 300, 375, and 450 K.

measurements, phase sensitive detection was used. For the photocurrent spectra white light was dispersed through a monochromator before being mechanically chopped and focused onto the device. To increase the signal-to-noise ratio for the high temperature multiplication, a 532 nm laser was used as the light source. An extrapolation of the unmultiplied primary photocurrent at low bias was used to account for changes in the carrier collection efficiency to accurately determine the gain [9].

The dark currents were measured for both structures as a function of diode area at room temperature. It was found that the current density did not scale with area, suggesting the dominance of large surface currents. These surface currents are most likely due to the fabrication processes, resulting in oxidation of the aluminum. For clarity only results for the 200 μm radius devices are presented in this Letter.

Figure 1 shows the *I*–*V* characteristics for PIN 1 and PIN 2 over a temperature range from 300 to 450 K. PIN 1 shows a sharp breakdown at 10.2 V, while PIN2 undergoes breakdown at 20.5 V. We have ruled out premature edge breakdown since similar gain was obtained when the position of the excitation laser spot was moved from the edge to the center of the diode as shown in the inset of Fig. 2. At room temperature the devices exhibit relatively large dark currents with values of tens of microamps prior to breakdown. The dark currents for both devices clearly increase as the temperature is increased; however, the current continues to scale with the device perimeter across this temperature range. This indicates that the dark current is still dominated by surface components, and as such it should be possible to reduce these with improved fabrication procedures.

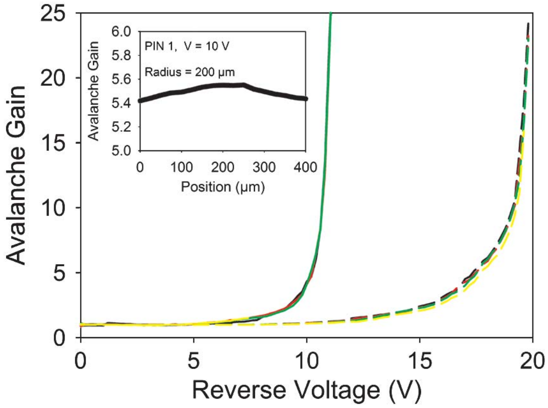

Fig. 2. (Color online) Avalanche gain for PIN 1 (solid curves) and PIN 2 (dashed curves) at temperatures of 300, 350, 400, and 450 K. Inset: avalanche gain as a function of position.

The voltage at which breakdown occurs shows only a slight change over this temperature range. Determining the change in breakdown from the *I*–*V* characteristics is problematic, as series resistance, surface leakage currents, and premature edge breakdown can all influence the measurements. To determine the absolute change in the breakdown with temperature, we have investigated the temperature dependence of the avalanche gain, M.

In Fig. 2 the avalanche gain for both devices can be seen at various temperatures. The curves exhibit a clear temperature insensitivity for both devices. The value of V_{bd} has been determined by linearly extrapolating the value of $1/M$ to 0, as shown in Fig. 3.

V_{bd} increases from 19.9 to 20.2 V in PIN 2 over this temperature range, corresponding to a C_{bd} of 1.93 mV/K. For PIN 1 V_{bd} increases from 11.15 to 11.29 V, giving an even smaller C_{bd} of 0.93 mV/K. These values agree well with those measured previously for AlAsSb at low temperatures [8]. Unlike Zener breakdown, which has a negative temperature coefficient, our positive C_{bd} confirms impact ionization as the breakdown mechanism. From this it can be concluded that avalanche photodiodes formed using AlAsSb can exhibit sub-millivolt per Kelvin changes in breakdown voltage between 77 and 450 K. These values are significantly smaller than those reported for InP and InAlAs diodes with comparable avalanche widths and studied only up to 375 K [10]. We believe this could be attributed to a combination of the large phonon energy and a high alloy scattering rate in AlAsSb. Detailed modeling of carrier transport is required to quantify these effects. We now focus our attention on the dependence of avalanche gain on carrier injection profile. First we measured the photocurrent as a function of wavelength at different values of reverse bias; the results for PIN 1 are shown in the inset of Fig. 4.

PIN 2 exhibited an identical shape in its spectrum with just an increased current due to higher absorption caused by the thicker i-layer. The material exhibits a peak photocurrent at 590 nm and has a cutoff wavelength

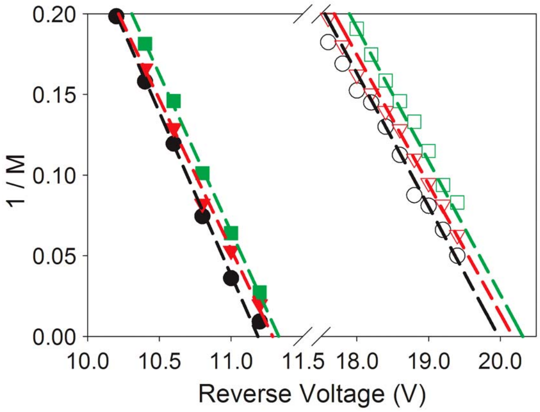

Fig. 3. (Color online) $1/M$ as a function of reverse voltage for PIN 1 (closed symbols) and PIN 2 (open symbols) at temperatures of 300 (circles), 375 (triangles), and 450 K (squares); the dotted lines show the linear extrapolations.

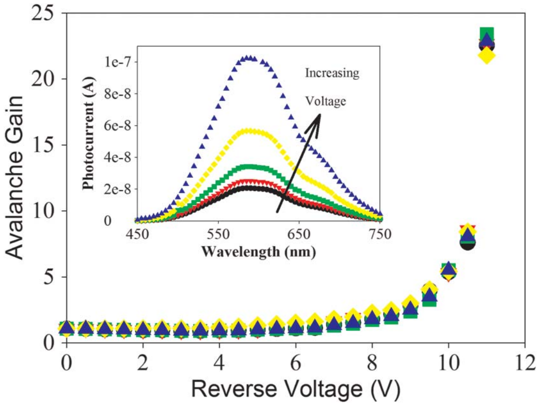

Fig. 4. (Color online) Avalanche gain for PIN 1 at wavelengths of 450 (circles), 500 (upside down triangles), 600 (squares), 700 (diamonds), and 750 nm (triangles). Inset: photocurrent spectra for PIN 1 at 0 (circles), 5 (upside down triangles), 7 (squares), 9 (diamonds), and 11 V (triangles).

at 780 nm (corresponding to a bandgap of 1.59 eV). By comparing the photocurrent at increasing values of reverse bias for a fixed wavelength, and correcting for the primary photocurrent at low voltages, it is possible to determine M at that wavelength.

Figure 4 shows that for PIN 1 the multiplication is virtually independent of the wavelength; the same results were also observed for PIN 2. As the excitation wavelength goes from shorter to longer wavelengths, the photons will travel further into the structure before they are absorbed. At short wavelengths all the photons will be absorbed in the top p-layer, leading to only electrons being injected into the multiplication region. At longer wavelengths the photons will also be absorbed in the i- and n-layers, leading to both electrons and holes initiating the multiplication process.

Although the absorption coefficients of AlAsSb are not well known, by linearly extrapolating between the absorption coefficients for AlAs [11] and AlSb [12], we estimated all the light to be absorbed within the p-region at a wavelength of 400 nm, while at a wavelength of 600 nm only $\sim 10\%$ of the injected light was absorbed in this layer, resulting in a mixed carrier injection profile. The relatively wavelength independent gain in Fig. 4 can only be achieved if the ionization coefficients for both electrons and holes are similar.

The sharp nature of the breakdown also suggests that the ionization coefficients are similar, resulting in strong feedback of carriers that causes the avalanche to rapidly increase in a runaway fashion. In conclusion, we have grown, fabricated, and characterized AlAsSb APDs. We have evaluated the temperature dependence of the multiplication and breakdown properties and shown that sub-millivolt per Kelvin changes are possible in the breakdown voltage up to temperatures of 450 K. We have also determined the avalanche gain as a function of wavelength, and from this we have determined that the impact ionization coefficients for electrons and holes are similar.

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