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Sensitivity Analysis of Si-Avalanche Photodiode for Noise Performance Assessment

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***Abstract*—Silicon avalanche photodiodes (APDs) play a key role in low-photon count electromagnetic wave detection applications, including single-photon (SPAD), night vision, and light detection and ranging. There is enormous potential to perfect existing APD designs by addressing limitations such as high-voltage breakdown, response time, and poor noise performance. We present a sensitivity-analysis-based method to capture the impact of temperature, bias voltage, and illumination power fluctuations on the noise performance of APDs. The study uses a well-calibrated ATLAS Silvaco framework utilizing our in-house experimental data. Using this well-calibrated framework, we study the impact of temperature, bias voltage, and illumination power variation on the response time of the APD. The dark current of APDs has an exponential relationship with temperature. In other studies, this increases the magnitude of dark current by 3-4 orders over a 100°C interval range. We show that a change of 10°C in temperature results in a ∼28% change in the fall time, a parameter that defines the operational 3dB bandwidth of the APD. The variation in bias voltage and illumination power is shown to impact the intensity of the response with ∼3% variation in the fall time. A study of this nature would enable the robust design of APD devices, ensuring reliable and efficient photon detection under low-light conditions.**

***Index Terms*—APD noise, APD reliability, sensitivity analysis, shot noise.**

I. INTRODUCTION

Silicon avalanche photodiodes (APDs) are paramount in advanced communication, detection, and imaging applications, such as fluorescence lifetime imaging, light detection and ranging, biomedical imaging, data communication, and hyperspectral imaging [1]–[3]. Constantly evolving research has enabled high-speed photodiodes by engineering doping stack profiles and introducing photon-trapping surface features to reduce the effective capacitance of the device [4]–[10]. Due to the analog nature of their operations, photodiodes are highly sensitive to systemic noise, which can significantly affect their performance. Therefore, accurate characterization and mitigation of these noise sources are essential for ensuring power-efficient signal processing with decent wavelength resolution in optoelectronic applications.

In this work, we conducted a parametric study to capture the effect of thermal noise, shot noise, and stochasticity introduced through bias voltage flickering. First, we calibrated the ATLAS Silvaco framework using our in-house experimental results on APDs [9], focusing on doping, breakdown voltage, and beam spot size for baseline APD performance. With this calibrated APD deck, we connected a passive resistor defined by a moderately n-type doped Si block in series to enable high-speed response simulation. We varied the temperature, illumination power, and bias voltage to capture the transient response variability. Our findings indicate that the APDs are most sensitive to thermal noise, followed by bias voltage, then illumination power variation. Using simulation results, we show that a 10°C change in temperature results in a ∼28% increase in the fall time of the APD, with a rapid increase in fall time at higher temperatures. Such parametric studies provide crucial insights into the noise tolerance level of an APD, a parameter essential for the design of APD-based imaging and communication systems.

II. SIMULATION SETUP

The silicon APD-resistor stack has been simulated using Silvaco ATLAS, a TCAD semiconductor device simulator. First, we calibrated the ATLAS deck using our in-house experimental dataset [9] for doping profile, breakdown voltage, and illumination beam spot size. Figure 1(a-b) presents a schematic of the APD and a direct-current (DC) current-voltage (I-V) profile showing a breakdown of 8.0 V in the dark and under the illumination of wavelengths ranging from 640–1100 nm, measured experimentally using a semiconductor parameter analyzer and NKT Supercontinuum Laser. The small-area Si-APDs are fabricated with co-planar waveguide (CPW) contacts for high-speed measurements. Figure 2(a) shows a microscopic image of the device under test probed with high-speed radio-frequency probes, and the inset shows the circuit arrangement used for the measurement. Figure 2(b) shows the high-speed response captured for a 20 μm diameter APD showing a response time of 27 ps, a fall time of 417 ps, and full-width half maxima (FWHM) of 209 ps.

The simulation deck calibration focuses on attaining the precise avalanche breakdown voltage by manipulating the P-on-N APD doping stack. We enabled impact ionization and band-to-band tunneling models to mimic the breakdown accurately. Using this calibrated APD deck, we simulated an APD-resistor circuit and captured the transient response of the assembly. The structure created was a P-on-N APD with the addition of an n-type substrate underneath the Si-APD for high-speed performance simulation. The framework required adding another terminal contact (*Vout*) apart from the top (cathode) and bottom (anode) as highlighted in Fig. 3(a). This allowed us to observe behavior

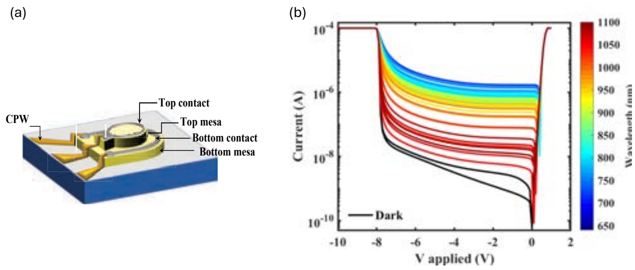

Fig. 1. (a) Schematic of silicon avalanche photodiode fabricated [9];(b) Direct-current current-voltage profile captured in the dark and under the illumination of wavelength ranging from 650 nm to 1100 nm. The bias voltage varies from 0 to 2 volts in the forward bias and 0 to -10 volts in the reverse bias.

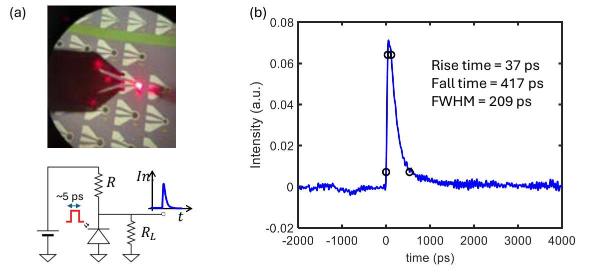

Fig. 2. (a) High-speed measurement setup and a microscopic image of the device under test; (b) transient response captured for a 30 μm Si-APD.

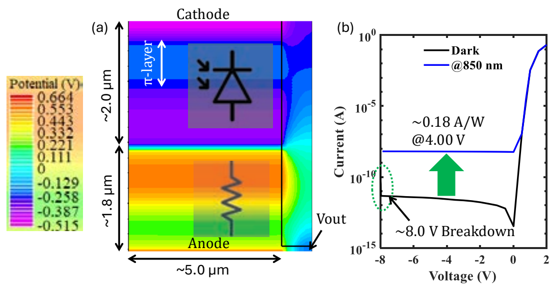

Fig. 3. (a) 2D Contour plot showcasing electrostatic potential profile in the APD-resistor circuit assembly simulated in ATLAS Silvaco platform; (b) DC I-V characteristics simulated in dark and under illumination of 850 nm wavelength.

at the anode and cathode contacts as well as the readout voltage at *Vout* during high-speed simulation. The P-on-N architecture begins with a P++ contact layer of thickness 100 nm with doping of 1.04×10^{19} cm^{-3}, the absorber (π) layer of thickness 800 nm with doping of 1.4×10^{15} cm^{-3}, followed by a P+ 200 nm layer with doping of 2.0×10^{17} cm^{-3}, and lastly a N++ contact layer of 1.0×10^{19} cm^{-3} with thickness of 100 nm. Figure 3(b) shows the DC I-V trend simulation in the dark and under the illumination of wavelength 850 nm and intensity $1\,\mathrm{W/cm^2}$ to highlight an 8.0 V breakdown and $\sim$0.18 A/W responsivity.

III. Parametric Analysis

We conducted a detailed parametric analysis to examine transient response parameters that may influence the high-speed performance of an APD, with a particular focus on identifying sources of noise and non-idealities. Parameters under investigation include response time, fall time, and full-width half maxima, with introduced variations in the bias voltage, temperature, and illumination power at a fixed wavelength of 850 nm. The nominal operating conditions were set at a temperature of 300K, an optical intensity of $1\,\mathrm{W/cm^2}$, and a bias voltage of 2 V, reflecting typical responses observed in our experimental data. For the dark current simulations, we employed reverse bias conditions. To investigate the effects of overheating, we varied the temperature across a wide range. Lastly, we adjusted the optical power and bias voltage within $\pm10\%$ of their nominal values to evaluate their impact on the APD's performance.

IV. Results and Discussion

The impact of temperature variation is presented in Fig. 4, where we varied the ambient temperature from 275K to 355K while maintaining a constant reverse bias of 2 V and optical intensity of $1\,\mathrm{W/cm^2}$ to capture the transient response of the APD-resistor circuit. We show that with a 10°C increase in temperature, the fall time, a parameter governing the 3dB bandwidth of the APD, increases by 28%, with a rapid increase at higher temperatures. This increase can be attributed to excess carrier generation at higher temperatures, which results in compromised carrier hole collection after the illumination is turned off. A similar response is observed when altering the bias voltage, where an 8.0% variation in the illumination intensity results in a negligible 0.003% variation in the fall time, as shown in Fig. 5(a). Lastly, a 10% bias voltage variation yields a 3% variation in the fall time, as shown in Fig. 5(b). As noted in other studies, the dark current of APDs exhibits a direct and exponential relationship with temperature, a trend observed in various materials such as germanium and InGaAs-InP [11], [12]. The temperature range examined was from 193K to 322K and correlations were found between temperature with respect to: reverse bias voltage and dark count probability [12]. For Si-APDs operating at similar wavelengths to our study [13], [14], it was shown that as temperature increases, the required breakdown voltage for operation also rises. Additionally, an increase in temperature leads to a corresponding rise in dark current in magnitudes of 3-4 for an interval of 100°C (373.15K) within the temperature range of 240K to 333K [11]–[14]. We can also correlate shot noise induced by dark current to its temperature dependence in APDs. While these studies considered broader temperature ranges, our focus was on a 10% fluctuation from the standard operating temperature. Parametric analysis of such nature is essential for power and speed efficient APD design for high-end optoelectronic applications.

V. Conclusion

We have discussed the design and sensitivity characterization of a Si-APD for a device illuminated in the near-

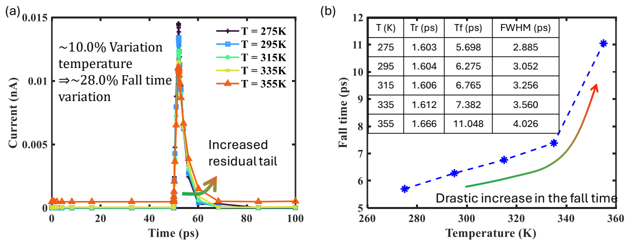

Fig. 4. (a) Transient response capture by varying the device temperature in the simulation setup at a fixed reverse bias voltage of 1 V, fixed illumination power of $1\,\mathrm{W/cm^2}$, and illumination wavelength of 850 nm; (b) Fall-time, a parameter governing the bandwidth of the APD is

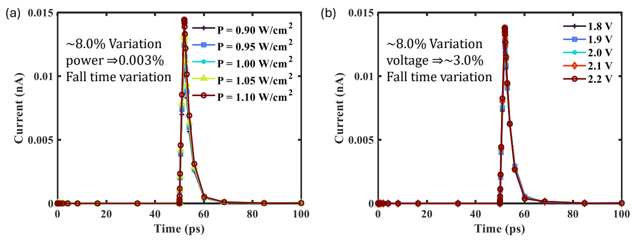

Fig. 5. Transient response simulated with (a) varying the illumination power and (b) the applied bias. Variation in the illumination power and the applied bias does not impact the fall time significantly.

infrared range under low-light conditions. We used an experimentally calibrated ATLAS Silvaco simulation deck to simulate APD-resistor transient performance variation with temperature, voltage, and illumination power fluctuation. We show that a 10°C change in temperature results in a 28% change in the fall time of the APD response after illumination is turned off. Additionally, an 8% variation in bias voltage and optical intensity results in 3% and 0.003% variation in the fall time of the APD, respectively. This indicates that the APD operation is primarily influenced by the ambient temperature, followed by the bias voltage, and then the intensity.

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