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Afterpulsing in Geiger-mode avalanche photodiodes for 1.06 μm wavelength

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We consider the phenomenon of afterpulsing in avalanche photodiodes (APDs) operating in gated and free-running Geiger mode. An operational model of afterpulsing and other noise characteristics of APDs predicts the noise behavior observed in the free-running mode. We also use gated-mode data to investigate possible sources of afterpulsing in these devices. For 30-μm-diam, 1.06-μm-wavelength InGaAsP/InP APDs operated at 290 K and 4 V overbias, we obtained a dominant trap lifetime of τ_d=0.32 μs, a trap energy of 0.11 eV, and a baseline dark count rate 245 kHz. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2189187]

Free-running Geiger-mode operation of avalanche photodiodes (APDs) provides a solid-state solution for efficient, high rate optical communication in the near infrared.[1] Applications such as quantum-key distribution use gated Geiger-mode operation, in which the APD is biased above its breakdown voltage at regular intervals at a low duty cycle [see Fig. 1(a)]. In the free-running mode the device is overbiased until an avalanche event occurs. At that time the bias is reduced below breakdown for a fixed hold-off time interval, t_{ho}, before rearming [see Fig. 1(b)]. The free-running mode maximizes the availability of the APD to detect photons and is critical for high data-rate communication. However, it requires that the APD be rearmed after as short a hold-off interval as possible. Afterpulsing sets a lower limit on this interval.

During an avalanche event, a small fraction of the charge carriers flowing through the device become trapped in energy states in the band gap.[2,3] After the event, the trapped states depopulate over time via field-assisted thermal excitation with a detrapping lifetime τ_d. If the APD is biased above breakdown before the traps have fully emptied, a detrapping carrier can initiate another avalanche, called an afterpulse. This phenomenon raises the effective count rate during the time shortly after the avalanche event, adding to the baseline dark count rate of the device. To avoid this effect, the APD cannot be rearmed until the traps have depopulated.[4] The loss of signal from this required hold-off time can be mitigated, however, by spreading the photon flux over several APDs such that the probability of a second photon illuminating the disarmed APD during its hold-off time is low.[1]

There are several processes that generate free carriers in the APD and can lead to an avalanche event. Random thermal and tunneling processes determine the baseline dark count rate R_{dark}. Absorption of background photons results in a background count rate R_γ. Similarly, absorption of signal photons results in a count rate R_s. Finally, afterpulsing adds a time-dependent contribution to the overall count rate. All of these can be modeled as Poisson processes with a combined time-dependent rate parameter,[5,6]

$$\lambda(t) = R_{\mathrm{dark}} + R_\gamma + R_s + P_a \frac{N_{\mathrm{ft}}}{\tau_d} \exp\left(-\frac{t+t_{\mathrm{ho}}}{\tau_d}\right), \quad (1)$$

where P_a is the probability that a single free carrier will trigger an avalanche and N_{ft} is the number of filled traps. This model does not take into account dark carriers generated before the device is biased above breakdown or linear multiplication of these carriers.[7] The model also assumes a single dominant trap. These additional terms could be added, but we found Eq. (1) was sufficient to model the behavior of our 1.06 μm APDs.

From Eq. (1), we obtain the mean time of the first APD avalanche event [with $t=0$ defined to be at the beginning of the bias gate; see Fig. 1(b)],

$$\langle t \rangle = \int_0^\infty t\lambda(t) \exp\left(-\int_0^t \lambda(t')dt'\right)dt. \quad (2)$$

We define the effective count rate as $1/\langle t \rangle$.

In order to test the model, we examined the afterpulse behavior of 1.06 μm InGaAsP/InP APDs operating in the gated and free-running modes.[6] We first extracted device parameters using a double gate method [see Fig. 1(c)]. A laser

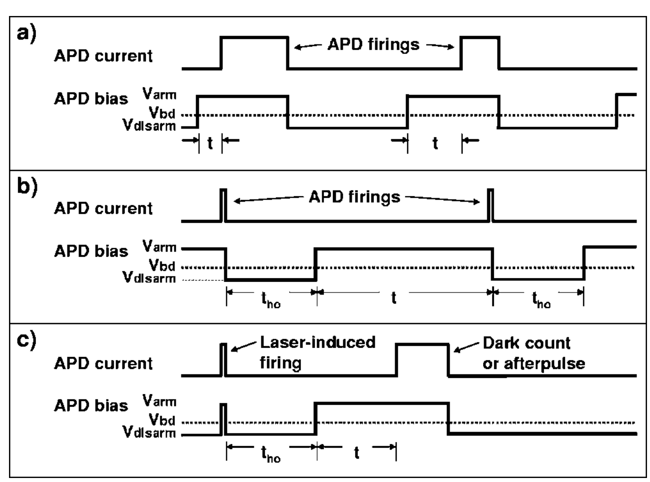

FIG. 1. Illustration of timing sequences of a Geiger-mode APD operating in (a) a gated mode, (b) a free-running mode, and (c) a double gated mode (not to scale).

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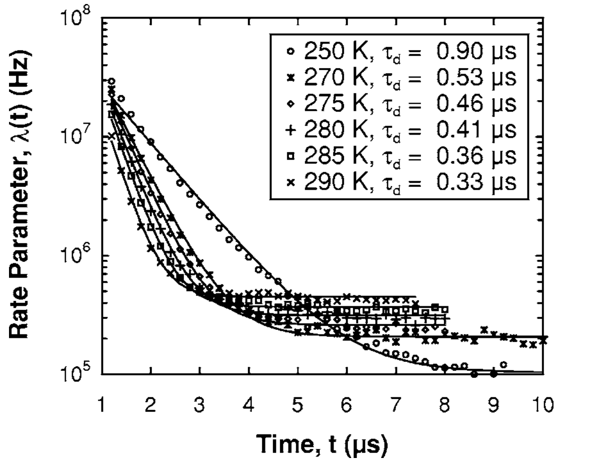

FIG. 2. $\lambda(t)$ vs time since laser-induced avalanche data (points) and fits (lines) to Eq. (1) for the gated-mode operation for temperatures ranging from 290 to 250 K. The extracted temperature-dependent detrapping time constant, τ_d, is also shown.

pulse triggers an avalanche event during the first gate, filling traps. The rate, $\lambda(t)$, of subsequent avalanche events is measured during a second, dark gate situated at varying delays after the first gate.

The baseline dark count rate of the devices tested varied from 245 to 600 kHz at 290 K and 4 V overbias, but all devices were very consistent in their afterpulse characteristics. From each device, the parameters τ_d, $P_a \cdot N_{\mathrm{ft}}$, and R_{dark} were extracted by fitting the count rate data from the double gate afterpulse experiment to Eq. (1). As there was neither signal nor background photon flux during the second gate, $R_\gamma = R_s = 0$. Figure 2 shows the gated-mode data for various temperatures, the corresponding fits, and the extracted τ_d for each temperature.

By systematically reducing the temperature from 290 to 250 K, we observed that R_{dark} decreased but τ_d increased. We also determined the activation energy, E_a, of the dominant trap that contributes to afterpulsing. We model the trap lifetime, τ_d, using the Arrhenius equation

$$\tau_d = \frac{1}{\sigma v N} e^{E_a/kT}, \quad (3)$$

where T is the temperature, σ is the trap cross section, $v = v(T)$ is the average thermal velocity of the carriers to be

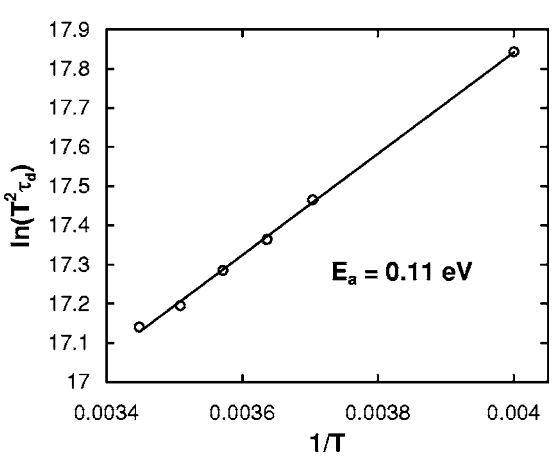

FIG. 3. Plot of $\ln(T^2\tau_d)$ vs $1/T$, from which E_a is extracted.

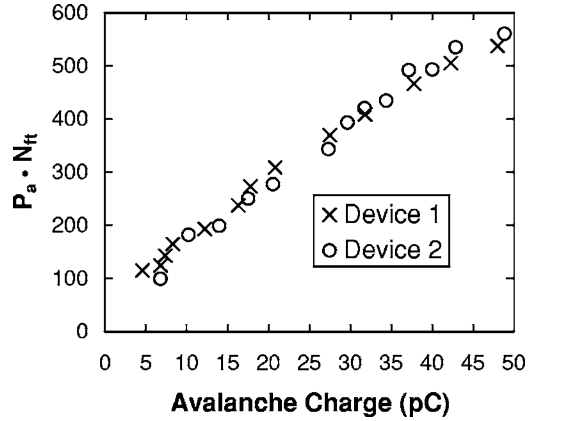

FIG. 4. Product of avalanche probability and number of traps filled vs charge flowing through the device during the laser-induced avalanche.

trapped, and $N = N(T)$ is the effective density of states of the relevant band (conduction band for electron traps, valence band for hole traps). We assume that $v \propto T^{1/2}$ and $N \propto T^{3/2}$, so that $\sigma v N$ has an overall temperature dependence of T^2. By plotting $\ln(T^2\tau_d)$ vs $1/T$ and performing a linear fit to the data, we were able to extract activation energy for the dominant trap of $E_a = 0.11$ eV. (See Fig. 3.) Native defects in InGaAsP/InP are being investigated as a possible source of this trap.

We also examined trap filling as a function of the charge flowing through a device during the initial, laser-induced avalanche. By varying the width of the first gate, we varied the net charge that flowed through the device. We then measured $\lambda(t)$ during the second gate for various charges. See Fig. 4 for a plot of the results for two devices. Note that N_{ft} is approximately linear with the avalanche charge in this range. This indicates that the number of traps filled is much smaller than the number of available trapping states. Also, it is possible to reduce the number of traps filled by simply reducing the charge that flows through an avalanching device. This can be accomplished by using fast-quenching circuits.

To test the model for free-running Geiger-mode device operation, we built a circuit to operate a device in this mode and to measure its afterpulse response. Using the parameters

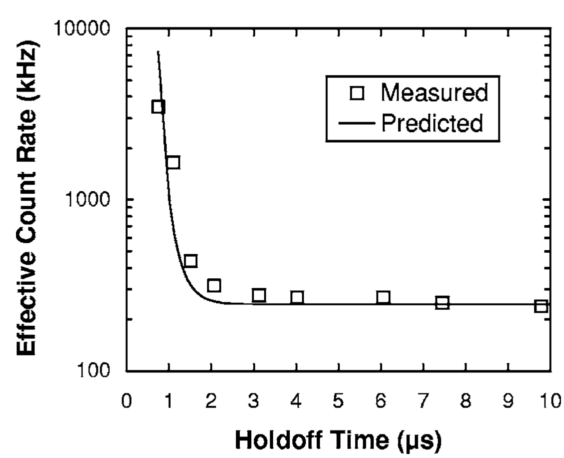

FIG. 5. Comparison of the measured effective dark count rate in the free-running mode at 293 K with model predictions. The model uses parameters extracted from the double gate experiment depicted in Fig. 1(c).

τ_d, $P_a \cdot N_{ft}$, and R_{dark} extracted from the gated-mode experiment with Eq. (2), we predicted the afterpulsing behavior of the device in the free-running mode at 293 K. Figure 5 compares the predictions of our model with the experimental data. Overall, we see good agreement between the predicted and actual count rates. However, the model does underestimate slightly near the bend in the data. One possible cause of this may be a secondary trapping state with a longer associated τ_d in addition to the dominant trapping state of the model. Note that Fig. 5 is for an APD in a discrete circuit with long leads and significant parasitic capacitance. By packaging the device in a lower-capacitance environment, as on a complementary metal-oxide semiconductor (CMOS) read-out circuit, the number of traps filled will be greatly reduced, and the holdoff will be correspondingly reduced.[8,9]

In conclusion, we have measured afterpulsing in free-running Geiger-mode APDs and used an operational model to predict device behavior in the free-running mode based on parameters extracted from the gated-mode operation. Also, we have used the gated-mode operation to study the traps that cause afterpulsing.

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