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Avalanche Noise Characteristics of Thin GaAs Structures with Distributed Carrier Generation

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***Abstract*—It is known that both pure electron and pure hole injection into thin GaAs multiplication regions gives rise to avalanche multiplication with noise lower than predicted by the local noise model. In this paper, it is shown that the noise from multiplication initiated by carriers generated throughout a 0.1 μm avalanche region is also lower than predicted by the local model but higher than that obtained with pure injection of either carrier type. This behavior is due to the effects of nonlocal ionization brought about by the dead space; the minimum distance a carrier has to travel in the electric field to initiate an ionization event.**

***Index Terms*—APD, avalanche multiplication, avalanche noise, GaAs, impact ionization.**

I. Introduction

In resonant cavity photodetectors a Fabry–Pérot cavity tuned to the absorption wavelength allows the use of a thin absorption region and thus reduces the primary carrier transit time without sacrificing quantum efficiency (QE). Furthermore if a separate multiplication region is also made sufficiently thin, the excess noise can be reduced significantly by nonlocal ionization effects [1]–[3]. Such resonant cavity enhanced, separate absorption and multiplication avalanche photodetectors (RCE-SAM-APD's) have been reported recently with high quantum efficiency and high gain bandwidth product [4], [5].

In SAM structures, both the layer width and the doping must be controlled to high precision. The absorption layer must be fully depleted to maximize the QE, however if the field is too high then multiplication can also occur in this region and the advantage of a separate thin multiplication region is reduced. The effect of distributed carrier generation, and so of "mixed" injection, on the noise characteristics of thin avalanching regions in which nonlocal ionization behavior reduces noise has not been investigated. If no appreciable degradation in noise characteristics occurs under such conditions, then a thin multiplication region could also be used as the absorption region to produce an RCE-combined-absorption-multiplication-APD (RCE-CAM-APD), with a less demanding layer structure.

In this paper, the effects of mixed injection on the multiplication and noise characteristics of a GaAs avalanche region nominally 0.1 μm in width are investigated and compared with the results for pure electron and hole injection. The experimental results are interpreted using a previously reported [2], [6] nonlocal recurrence theory for uniform avalanche regions which is extended here to treat devices with an arbitrary carrier injection profile.

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II. Growth and Device Fabrication

The structure shown in Fig. 1 was grown as an RCE-APD by metal organic vapor phase epitaxy using C and Si as the p^+ and n^+ dopants and was designed to have a high QE at an incident wavelength of 850 nm. However in this study it is not used in resonance and can be regarded as a $p^+(Al_{0.5}Ga_{0.5}As)$-$i(GaAs)$-$n^+(Al_{0.5}G_{0.5}As)$ diode with a thin $Al_{0.2}Ga_{0.8}As$ capping layer. Two GaAs homojunction structures, one p^+-i-n^+ and the other a n^+-i-p^+ were also grown by molecular beam epitaxy on $n^+(p^+)$ (001) GaAs substrates and comprised an $n^+(p^+)$ GaAs buffer, an $n^+(p^+)$ AlAs 0.1 μm etch stop layer, 1 μm of $n^+(p^+)$ GaAs, an undoped GaAs avalanche region of width, $w = 0.1$ μm and finally a 1 μm GaAs $p^+(n^+)$ layer. Circular mesa diodes of radius 50–200 μm and with annular top contacts for optical access were fabricated from these layers. Dark current measurements on the RCE-APD devices showed low leakage currents of ~200 nA at 90% of the breakdown voltage on the 100 μm radius devices.

III. Measurements

Avalanche multiplication measurements were performed using a noise measurement system with a center frequency of 10 MHz and a noise effective bandwidth of 4.2 MHz [2]. Carrier injection was provided by 442 nm, 542 nm, or 633 nm lasers focused to a spot onto the top $p^+(n^+)$ capping layer. The excess noise factor, F, was determined from the noise power measurements using the method described previously [2] and was calculated from $F = i_{\mathrm{eq}}/M^2 i_p$, where M is the mean multiplication, i_p is the unmultiplied primary photocurrent and i_{eq} is the equivalent photocurrent of the silicon p-i-n diode that produces the same noise power as the device under test.

Light of wavelength 633 nm, to which the $Al_{0.5}Ga_{0.5}As$ p^+ and n^+ layers are almost transparent, was used to produce mixed injection in the RCE-APD. Most carriers generated in the thin $Al_{0.2}Ga_{0.8}As$ p^+ layer, the Bragg mirrors and the substrate recombine before diffusing to the high field region. The 633 nm light is absorbed in the GaAs i-region and generates carriers in a distributed manner throughout this region; only these carriers contribute to multiplication. Illuminating with a He-Cd laser at

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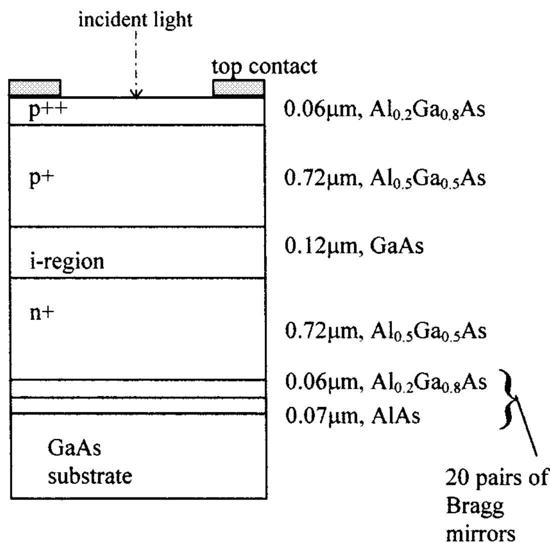

Fig. 1. RCE-APD structure used for mixed carrier initiated multiplication.

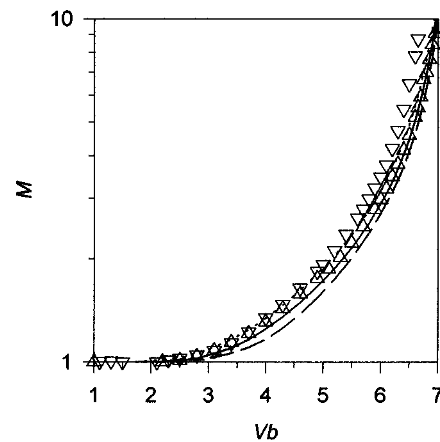

Fig. 2. Multiplication versus reverse bias for the RCE-APD at incident wavelengths of 442 nm (-----), 542 nm (—) and 633 nm (———). Also shown is photomultiplication for pure electron (△) and hole (▽) injection in the 0.1 μm GaAs p^+-i-n^+ and n^+-i-p^+ diodes respectively.

442 nm produces nearly pure electron injection since the light is highly absorbed in the $Al_{0.5}Ga_{0.5}As$ p^+ layer and photogenerated minority electrons diffuse to the high field region. For the intermediate incident wavelength of 542 nm some light is absorbed in the p^+ region and some in the i-region resulting in distributed mixed injection with a significant contribution of electrons injected from the p^+ $Al_{0.5}Ga_{0.5}As$ layer. In contrast, in the homojunction GaAs p^+-i-n^+ (n^+-i-p^+) diodes, light incident at wavelengths of 633 nm, 542 nm, and 442 nm is almost completely absorbed in the 1 μm capping layer producing electrons (holes) that diffuse to the high field region, resulting in pure electron (hole) initiated multiplication.

Fig. 2 shows the multiplication characteristics for the RCE-APD at incident wavelengths of 442 nm, 542 nm, and 633 nm. It can be seen that, for the same reverse bias voltage, the multiplication in the RCE-APD with 442 nm incident light is higher than that at 542 nm which is, in turn, higher than at 633 nm. The GaAs p^+i-n^+ and n^+-i-p^+ diodes each produced identical multiplication characteristics with 633 nm, 542 nm and 442 nm incident light and so, for clarity, only the 633 nm multiplication characteristics are shown.

The multiplication characteristics of the RCE-APD at 442 nm are very similar to those of the GaAs p^+-i-n^+ diode at 633 nm, suggesting that pure electron initiated multiplication has been achieved. The RCE-APD breakdown voltage is 7 V, identical to that of the $w = 0.1$ μm p^+-i-n^+ diode, suggesting that although the RCE-APD was grown to a width of nominally $w = 0.12$ μm it is closer to $w = 0.1$ μm. The breakdown voltage of the n^+-i-p^+ diode was ~6.5 V suggesting that the device is slightly thinner than 0.1 μm, as confirmed by analysis of the capacitance voltage measurements and secondary ion beam mass spectroscopy profiles.

Fig. 3 shows plots of excess noise versus multiplication for the RCE-APD and the GaAs p^+-i-n^+ (n^+-i-p^+) diode together with McIntyre's [8] curves for various values of $k = \beta/\alpha$, where α and β are the electron and hole ionization coefficients, respectively. However, since McIntyre's continuum theory does not apply in the limit of very thin avalanche regions, these curves are included solely for the purposes of comparison.

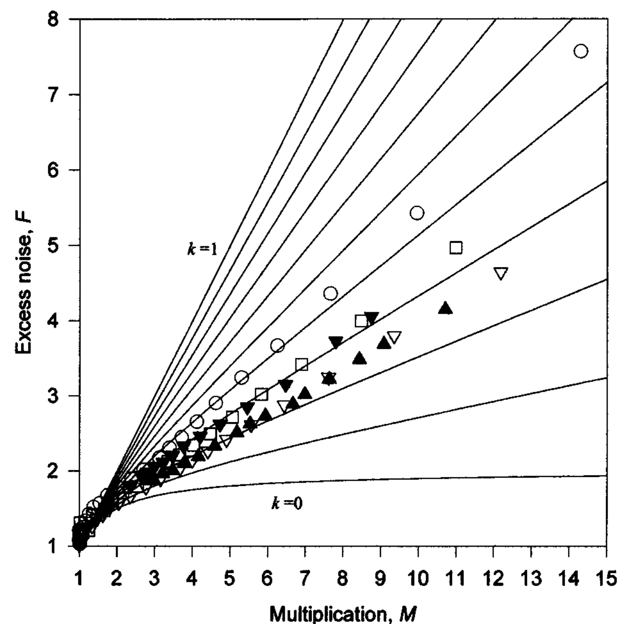

Fig. 3. Excess noise factor versus multiplication for the RCE-APD at incident wavelengths of 442 nm (▽), 542 nm (□) and 633 nm (o), and for the $w = 0.1$ μm GaAs p^+-i-n^+ (▼) and n^+-i-p^+ (▲) diodes using 633 nm wavelength light. Solid lines are McIntyre's curves with $k = \beta/\alpha$ increasing from 0 to 1 in steps of 0.1.

With 633 nm light incident on the RCE-APD, primary carriers are generated in the high field region and the resulting noise characteristics shown in Fig. 3 correspond approximately to $k \sim 0.4$ in McIntyre's model [8]. For the more energetic incident light of 542 nm and 442 nm the noise characteristics decrease to levels corresponding to $k \sim 0.3$ and $k \sim 0.25$, respectively. Also plotted in Fig. 3 are the pure electron and hole initiated multiplication noise characteristics of the GaAs p^+-i^+ and n^+-i-p^+ diodes using 633 nm light. Unlike in the RCE-APD, illuminating the GaAs p^+-i-n^+ (n^+-i-p^+) diodes

with 542 nm and 442 nm light produced identical noise characteristics to those obtained with 633 nm excitation. The pure electron injection noise results for the p$^+$-i-n$^+$ diode are almost identical to those of the RCE-APD obtained using 442 nm light, further confirming that, as expected, pure electron injection has been achieved in the RCE-APD. However, with 633 nm light and mixed carrier injection, the RCE-APD exhibits noisier characteristics than either the pure electron or pure hole initiated multiplication results.

IV. Modeling

It is worth considering how the gain and excess noise characteristics would behave in thick ($\sim$1 μm) GaAs structures, where the local model of McIntyre [8] is applicable. At the operating field of such structures $\alpha \approx 2\beta$, and pure electron initiated multiplication, M_e, is greater than pure hole initiated multiplication, M_h. The excess noise results would follow the $k = 0.5$ line in Fig. 3 with electron initiated multiplication (F_e) and the $k = 2$ line with hole initiated multiplication (F_h). For carrier generation within the high field region the gain and excess noise curves would lie between those of M_e and M_h, and between those of F_e and F_h, respectively. In thin GaAs structures, $M_e \sim M_h$ [9] and the slight discrepancies in the p$^+$-i-n$^+$ and n$^+$-i-$^+$ multiplication characteristics in Fig. 2 are the result of the slight difference between the avalanche widths. According to the local model when $\alpha \approx \beta$ then $F_e \sim F_h$, corresponding to $k = 1$ in Fig. 3. In this case, distributed carrier generation would give results indistinguishable from those of pure injection for both gain and excess noise. By contrast a reduction in gain and an increase in excess noise with distributed carrier generation is observed in the RCE-APD.

To interpret the mixed injection results a model is used which has previously been shown to predict accurately the avalanche multiplication and noise characteristics of GaAs p$^+$-i-n$^+$ and n$^+$-i-p$^+$ diodes. This model has been described in detail in [6] for the case of pure electron (hole) injection and is developed here to predict the noise produced from mixed carrier injection. An ideal p$^+$-i-n$^+$ structure is assumed, with a uniform high field region in $0 < x < w$ and no depletion into the p$^+$ and n$^+$ cladding regions. Newly generated electrons (holes), produced either by injection into the high field region or as by products of impact ionization, travel in the electric field, ε, a distance d_e (d_h), equal to their dead space, before they are able to ionize. The dead space values are taken as:

$$d_e = E_e/e\varepsilon \tag{1a}$$

$$d_h = E_h/e\varepsilon \tag{1b}$$

where $E_e = 2.3$ eV ($E_h = 2.1$ eV) is the ionization threshold energy for electrons (holes) and e is the unit of electronic charge. Following the dead space, the carrier ionization behavior is described by an exponentially decaying spatial probability distribution function (PDF) for ionization path length, x, corresponding to the ionization coefficients α^* and β^* as in [6]. The PDF is thus given by

$$h_e(x) = \begin{cases} 0, & x < d_e \\ \alpha^* \exp(-\alpha^*(x - d_e)), & x \geq d_e \end{cases} \tag{2}$$

for electrons. An expression for the hole PDF for ionization path length, $h_h(x)$, is obtained by replacing d_e and α^* with d_h and β^*.

The values of α^* and β^* are found from the relationships [10]

$$\alpha^{-1} = d_e + \alpha^{*-1} \tag{3a}$$

$$\beta^{-1} = d_h + \beta^{*-1} \tag{3b}$$

and the experimental ionization coefficients, α and β. These are taken from the work of of Bulman *et al.* [11] for $\varepsilon > 600$ kV/cm, and from the work of Millidge *et al.* [12] for $\varepsilon > 600$ kV/cm with β set equal to α. α and β are interpolated around $\varepsilon = 600$ kV/cm to produce a smooth transition from the data of Bulman to Millidge. The coupled integral (10) and (11) from [6] are then used to calculate the mean gain, and (18) and (19), also from [6], are used to calculate the excess noise. These coupled equations are discretized on a suitable mesh and the resulting linear simultaneous equations are solved to deduce the mean multiplication, $m(x)$, and the excess noise factor, $F(x)$, for a primary electron-hole pair created at position x in the high field.

In the RCE-APD structure photons are absorbed throughout the high field region at a rate given by the function $G(x)$. Using the solutions for $m(x)$ and $F(x)$, the total multiplication, M_T, and total excess noise, F_T, for any spatially distributed generation rate of carrier pairs can be derived.

For a nonavalanching photodiode, the noise spectral density from primary carriers generated in an element dx, due only to shot noise, is given by

$$dN_s(x) = 2e[G(x)e\,dx] \tag{4}$$

where $e =$ the unit of electron charge.

In the case of an avalanching photodiode, where the primary current is generated throughout the avalanche region before being collected at the device terminals, the spectral noise current density is multiplied by $m^2(x)$ and given by

$$dN_{ms}(x) = 2e[G(x)e]m^2(x)\,dx. \tag{5}$$

However, the above equation treats $m(x)$ purely as a gain term and does not allow for the fact that $m(x)$ is stochastic in nature. To do so, the excess noise factor for an electron hole pair generated at position x is introduced, which gives

$$dN_T(x) = 2e[G(x)e]m^2(x)F(x)\,dx. \tag{6}$$

To find the total noise due to the distributed generation of primary carriers we integrate over the avalanche region giving

$$N_T = 2e^2 \int_0^w [G(x)m^2(x)F(x)]\,dx. \tag{7}$$

The multiplication is defined by the total multiplied output current divided by the total unmultiplied input current and given by

$$M_T = \frac{\int_0^w G(x)m(x)\,dx}{\int_0^w G(x)\,dx}. \tag{8}$$

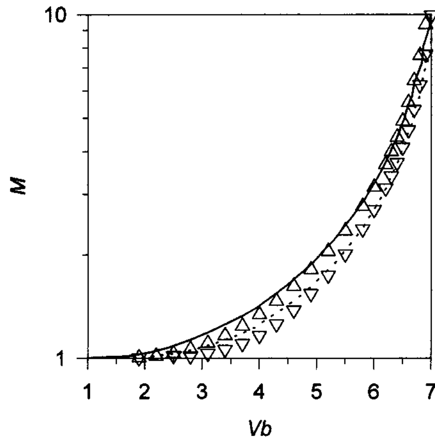

Fig. 4. Multiplication versus reverse bias for the RCE-APD at incident light wavelengths of 442 nm (————, $\triangle$) and 633 nm (- - - - -, ∇). Lines represents calculations and symbols the experimental results.

An ideal APD would therefore produce a noise power spectral density, due only to multiplied shot noise, of

$$N_{\text{ideal}} = 2ei_{\text{pr}}M_T^2 = 2e^2M_T^2 \int_0^w G(x)\,dx. \tag{9}$$

Hence, the excess noise factor for a distributed generation of carriers is

$$F_T = \frac{N_T}{N_{\text{ideal}}} = \frac{\int_0^w G(x)m^2(x)F(x)\,dx}{M_T^2 \int_0^w G(x)\,dx}. \tag{10}$$

The modeled and experimental multiplication and noise characteristics of the RCE-APD are plotted in Figs. 4 and 5 for the cases of pure electron initiated multiplication (442 nm) and for a distributed generation rate of carriers in the high field region (633 nm). The generation rate for mixed injection is taken as $G(x) \propto \exp(-\phi x)$, where $\phi = 4.28 \times 10^4$ cm^{-1} is the absorption coefficient of GaAs at 633 nm [7].

It can be seen in Figs. 4 and 5 that the modeled multiplication and noise characteristics (solid symbols) match closely the measured results (open symbols). The modeled results are slightly higher, possibly because of the simplified choice of PDF in (2). To explain the reason for the higher noise characteristic in the case of mixed injection, plotted in Fig. 6(a) is the multiplication, $m(x)$, and excess noise, $F(x)$, for an electron hole pair injected at a position x at an electric field of 750 kV/cm at which α and β are equal.

Fig. 6(a) includes the special cases of pure electron initiated multiplication, $M_e = m(0)$ and $F_e = F(0)$, and of pure hole initiated multiplication, $M_h = m(w)$ and $F_h = F(w)$. As the position, x, at which an electron-hole pair is created is moved into the high field region the multiplication initially decreases, falling to a minimum value at $x = 28$ nm. Thereafter, it rises to a peak close to the middle of the avalanche region, at $x \sim 50$ nm and then falls again, reaching a second minimum at $x = 70$ nm. Finally, the multiplication rises to the value of M_h at $x = w = 100$ nm. This result contrasts with the local model [13] in which $m(x)$ is independent of position when $\alpha = \beta$. The two minima, one at 28 nm and the other at 70 nm, correspond to the hole and electron dead space distances from the edges of

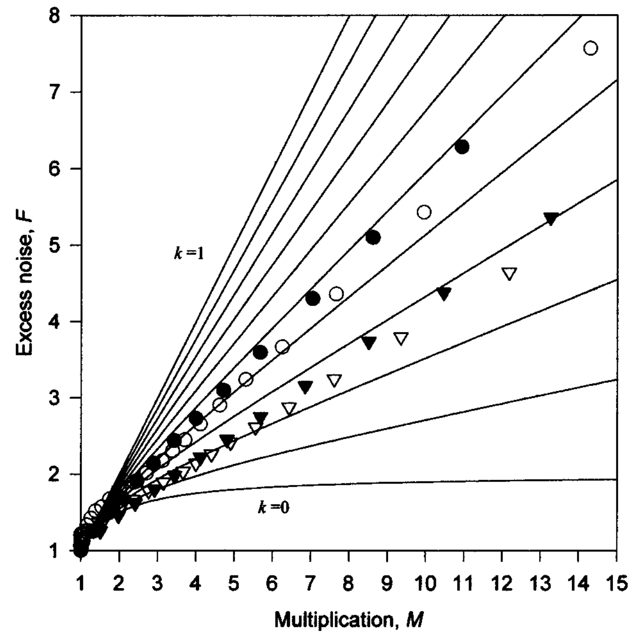

Fig. 5. Excess noise factor versus multiplication for the RCE-APD at incident light wavelengths of 442 nm (∇, $\blacktriangledown$) and 633 nm ($\bigcirc$, $\bullet$). Open symbols are the measurements and solid symbols the modeled results. Solid lines are as in Fig. 3.

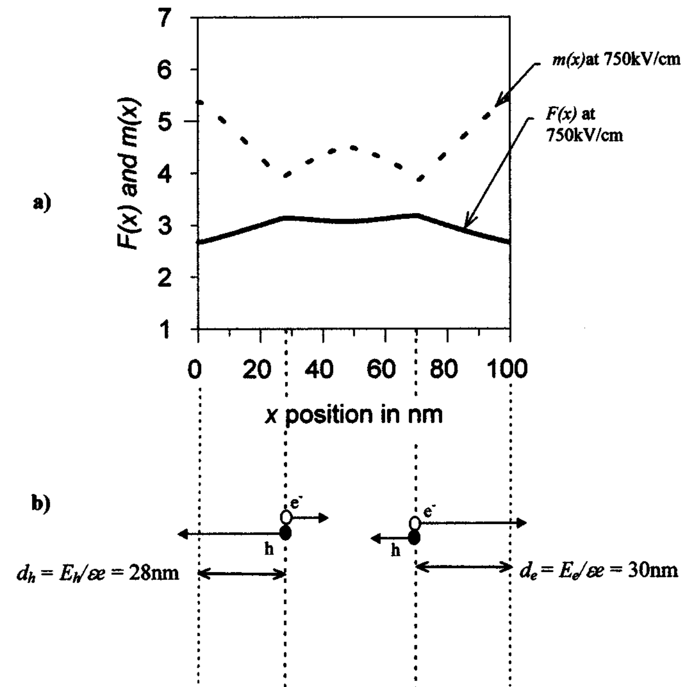

Fig. 6. (a) Multiplication $m(x)$ and excess noise, $F(x)$ for an electron hole pair generated at a position x in the high field region ($0 < x < w$) at an electric field of 750 kV/cm. (b) Schematic of an electron hole pair generated at $x = 28$ nm and $x = 70$ nm.

the high field region. As depicted in Fig. 6(b), if an electron-hole pair is created at $x \leq 28$ nm only the electron contributes to multiplication since the hole will leave without ionizing, similarly if an electron-hole pair is generated at $x \geq 70$ nm, only the hole contributes to multiplication while the electron leaves without ionizing. Hence, at these minima multiplication is reduced because only one carrier type can go on to ionize and contribute

to multiplication. Consequently, a distributed generation of primary carriers in the high field produces a lower multiplication for the same electric field than pure electron or hole injection.

The excess noise, $F(x)$, is shown in Fig. 6(a) and also depends on the primary carrier injection position x. At $\varepsilon = 750$ kV/cm it is lowest when $x = 0$, $x = w$ and $x = 50$ nm and higher at $x = 28$ nm and $x = 70$ nm, the electron and hole dead space separation, respectively, from the edge of the high field region. This contrasts with the predictions of McIntyre's local noise model [8] in which $F(x)$ is independent of position when $\alpha = \beta$. A distributed generation of carriers in the high field region will therefore produce a worse noise characteristic than either pure electron or pure hole injection.

V. Conclusion

In thin GaAs avalanche regions ($\sim$0.1 μm) a distributed generation of primary carriers in the high field region is found to produce lower gain and higher noise than obtained with pure electron or pure hole initiated multiplication. The implications for device design are that it is still necessary to ensure pure carrier injection for the lowest noise in such structures. However, even in the case of mixed injection, the noise in thin structures still compares favorably with that achievable in thick ($\sim$1 μm) GaAs avalanche regions. Reducing the absorption-multiplication width further in the RCE-CAM-APD should further decrease the excess noise but an increase in dark current due to tunneling will prove to be a limiting factor.

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Keng Y. Chang, photograph and biorgraphy not available at the time of publication.

John S. Roberts, photograph and biorgraphy not available at the time of publication.