High-sensitivity, wide-dynamic-range avalanche photodiode pixel design for large-scale imaging arrays

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Abstract. We present a detailed design study for a novel solid-state focal plane array of silicon avalanche photodiodes (APDs), with each detector in the array capable of operating with wide dynamic range in linear or Geiger-mode. The detector array is based on back-illuminated, crystallographically etched, (100) epitaxial silicon on R-plane sapphire substrates using 27 μm pixels, although other sizes could be supported as well. Analysis of the APD pixel design, which includes the photoelectron noise, dark current noise, and electronic circuit noise, shows the capability of imaging with a signal-to-noise ratio greater than 7 at −30 °C and ultralow illumination of 10^{-4} lux. The detector array design will enable large focal planes, capable of imaging with high sensitivity and high speed, over a wide range of natural illumination conditions from direct sunlight to a cloudy moonless night.

1 Introduction

There is a growing need in science and industry for large-scale detector arrays capable of imaging with high sensitivity and high speed near room temperature, over a wide range of natural illumination conditions from direct sunlight to a cloudy moonless night. Existing solid-state camera technology does not enable imaging in the visible spectrum over such a wide dynamic range near room temperature. In this design study, we demonstrate through detailed calculation means that a novel back-illuminated, wide dynamic range avalanche photodiode (APD) device design will enable imaging with high sensitivity near room temperature at −30 °C, over the full range of natural illumination conditions from the AM 0 in space orbit around Earth, to ultralow light levels when the illuminance at the camera lens E_{L}=0.0001 lux [lumens/m^2], as on a cloudy moonless night when far from city lights. The high pixel sensitivity is achieved using a compact readout circuit, capable of controlling detector operation in linear and Geiger-mode regimes. The proposed wide dynamic range APD detector can operate in full depletion mode in the linear regime, when biased 8 V below the 36 V reverse breakdown voltage to support high quantum efficiency and speed. When charged to 44 V reverse bias, the detector design was shown in Ref. 1 to support Geiger-mode, and the efficiency of collecting photogenerated electrons to produce detection events was evaluated by Monte Carlo simulation to be above 80% for wavelengths between 300 and 800 nm.¹

The silicon APD array was designed with square pixels of 27 μm side length for high resolution imaging with 100% sensitive-area-fill-factor, on a mechanically rugged and optically transparent sapphire substrate. When (100) silicon is properly etched with potassium hydroxide:isopropyl alcohol:water (KOH:IPA:H₂O) or tetramethylammonium hydroxide (TMAH) solution through a thermally grown oxide mask, square-based pyramidal frustum or mesa arrays result with the four mesa sidewalls of the APD formed by (111) silicon planes that intersect the (100) planes at a crystallographic angle ϕₖ=54.7 deg. The APD would be fabricated in the mesa using conventional silicon processing technology. The proposed APD design enables operation over a wide dynamic range in linear mode with or without internal gain for passive imaging in daylight conditions, and in single-photon sensitive Geiger-mode for active or passive imaging under low-light level conditions.¹² The detector is back-illuminated through a light focusing spherical microlens fabricated in the thinned sapphire substrate that directs light toward the device interior and away from the silicon mesa sidewalls, thereby compensating the optical dead space between pixels resulting from the mesa isolation etch and also from the internal device guard diode geometry.

The sapphire microlenses can be coated with an antireflective λ/4-MgF₂ layer, for example, to improve the optical power transmittance from air into the sapphire. In addi-
tion, a lattice-matched (AlN) antireflective crystal layer can be grown on the sapphire-silicon interface to further increase the optical power transmittance into the device sili-
con, as shown in Fig. 1 and described in Ref. 2. The APDs in the array share a common, front-side anode contact, made locally at the base of each device mesa. A low resis-
tance aluminum (Al) or copper (Cu) metal anode grid fills the space between pixels and also functions to inhibit optical
crosstalk by shielding adjacent detectors from stray photons generated during the avalanche process.\(^3\) SOS-
APD arrays are indium bump-bonded to complementary metal oxide semiconductor (CMOS) readout ICs to produce hybrid focal plane arrays (FPAs), as shown in Fig. 2, which might be 1024×1024 pixels or larger.\(^4\) The camera lens focal length and focal ratio maintain 100% sensitive-area-
fill-factor over the full FPA active area by limiting the maximum incidence angle of the extreme rays shown in red in Fig. 2, incident at the microlens edges of the pixel, lo-
cated farthest from the camera optic axis at the corner of the FPA.\(^2\)

The silicon APD is designed with a carefully optimized high electric field multiplication region, fabricated by high temperature diffusion of boron, described in Ref. 1. The boron impurity profile determines the spatial electric field in the device, and the boundary between the low electric field absorption-collection region and the high electric field multiplication region, as well as the APD guard diode geometry described by the guard diode boundary function \(f_{GP}(x,y)\), are shown in Fig. 1. The narrow, high electric field multiplication region and the much wider low electric field collection-absorption region, help to provide stable, uniform gain with minimum variance, for nearly all of the photogenerated electrons in the device. Since most electron-hole pairs (EHPs) are generated through light ab-
sorption outside of the multiplication region, this results in a low excess noise factor for the APD.\(^5\)–\(^7\)

2 Device Characteristics of Wide Dynamic Range Avalanche Photodiode

The silicon-on-sapphire material system was originally de-
veloped for integrated circuit applications; however, it also has many ideal attributes for use as a substrate, enabling back-illuminated, solid-state, silicon detector arrays. Sap-
phire is an anisotropic, dielectric crystal of the negative uniaxial type that is weakly birefringent \((n_\rho/n_\theta=0.008)\) and possesses broadband optical transmittance ranging from the deep ultraviolet \((\lambda_\rho=200 \text{ nm})\) to the midwave IR \((\lambda_\theta=5500 \text{ nm})\). Sapphire is extremely resilient, supporting thinning below 100 \(\mu\text{m}\), which is an important requirement for high resolution back-illuminated detector arrays. SAPh-
phire can be optically polished to better than an 80 to 50 (scratch-dig) surface finish and can be etched optically us-
ing 157 nm excimer laser ultraviolet light to fabricate light focusing microlenses for the silicon detectors. Sapphire is chemically resistant to most liquid etchants at room tem-
perature, and therefore functions as an ideal etchstop mate-
reral during liquid crystallographic etching with (KOH:IPA:H\(_2\)O) or TMAH solution to define the silicon pixel mesa arrays. To enable high quantum efficiency back-
illuminated silicon detector arrays, the refractive index mis-
match between air, sapphire, and silicon has to be cor-
rected. The wide bandgap semiconductor material aluminum nitride (AlN) is closely lattice matched and re-
fractive index matched to both sapphire and silicon, and offers the prospect of enabling fabrication of high transmis-
tance (100) silicon-on-(AlN)-sapphire substrates for back-
illuminated silicon imagers.\(^8\)–\(^10\)

The APD in Fig. 1 has been designed for wide dynamic range operation by allowing the polysilicon cathode to ex-
tend beyond the edges of the mesa top over the thermally grown passivation oxide to form an MOS capacitor that acts as a charge-coupled device (CCD) gate. When the APD is reverse biased, the combination of the APD \(p/n\)-junction and the MOS capacitor formed by the over-
hanging polysilicon operates similarly to the input diode and input gate of a CCD.\(^11\) When the wide dynamic range APD in Fig. 1 is reverse biased at voltages well below the reverse breakdown voltage of the detector, the \(p/n\)-junction

\[\text{Fig. 1 Advanced back-illuminated, crystallographically etched silicon-on-(R-plane) sapphire APD device for arrays showing a monolithically integrated sapphire microlens and } \lambda/4-\text{MgF}_2 \text{ and AlN antireflective layers.}\]

\[\text{Fig. 2 Back-illuminated, silicon-on-sapphire APD array chip, bump-}
\text{bonded to CMOS readout IC. Extreme rays (shown in red) are inci-
dent at the maximum incidence angle } \theta_{\text{inc, max}} \text{. (Color online only.)}\]

\[\text{Journal of Electronic Imaging 021102-2 Apr–Jun 2010/Vol. 19(2)}\]
cannot deplete fully to the silicon-sapphire interface due to blocking by the high electric field boron impurity diffusion. However, the polysilicon MOS capacitor can deplete into the $p$-type silicon fully to collect any photogenerated electrons in the device. The APD $p/n$-junction prevents an inversion layer from forming under the polysilicon CCD gate by collecting the photoelectrons under the gate, producing an unmultiplied photocurrent. Therefore, at low reverse bias voltages, the polysilicon MOS capacitor depletes deep into the silicon to collect photogenerated electrons, which are in turn collected by the cathode of the APD $p/n$-junction, bypassing the high electric field region of the APD without being multiplied. At low reverse bias, the photogenerated electrons are mainly directed toward the MOS capacitor at the periphery of the device and relatively few photogenerated electrons in the APD reach the high electric field multiplication region. Therefore, the internal gain of the device remains low, even though the electric field in the multiplication region might reach the critical value of \( E_{\text{critical}} = 3 \times 10^5 \text{ V/cm} \) in silicon required for impact ionization. The region at the periphery of the device is indicated as a guard diode, because its purpose is to collect surface generated electrons. The electrons collected at the periphery will have reduced probability of drifting to the high field region to be multiplied. When the APD is biased above the reverse breakdown voltage, a much larger fraction of photogenerated electrons are directed toward the multiplication region of the device than at lower bias voltages, resulting in larger internal gain. For both linear and Geiger-mode operation, the device silicon will be fully depleted to enable efficient collection of photogenerated electrons from the entire silicon volume. These results were confirmed through extensive device simulations using MEDICI software of mesa APD structures created using the TSUPREM 4 fabrication simulation software as described in Refs. 1 and 2.

### 2.1 Calculated Photocurrent of Wide Dynamic Range Mesa Avalanche Photodiode

The sensitivity of the wide dynamic range APD in Fig. 1 can be evaluated by considering that the silicon detector images primarily over the visible wavelength range. Manufacturers of commercial consumer cameras that detect primarily in the visible spectral range often describe the camera sensitivity by specifying the minimum illuminance condition at the entrance aperture of the camera in photometric units of lux required to capture an image with clarity. Table 1 lists illuminance values for different imaging conditions.12

<table>
<thead>
<tr>
<th>Illuminance ($E_l$)</th>
<th>Lux [lumens/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct sunlight at noon, very clear day</td>
<td>50,000 to 130,000</td>
</tr>
<tr>
<td>Daylight, sunny day</td>
<td>15,000</td>
</tr>
<tr>
<td>Daylight, cloudy</td>
<td>2,000</td>
</tr>
<tr>
<td>One hour before dusk</td>
<td>200</td>
</tr>
<tr>
<td><strong>Dusk</strong></td>
<td>10</td>
</tr>
<tr>
<td>Late dusk</td>
<td>1</td>
</tr>
<tr>
<td>Clear night, full moon</td>
<td>0.1</td>
</tr>
<tr>
<td>Clear night, quarter moon</td>
<td>0.03</td>
</tr>
<tr>
<td>Starlight, no moon</td>
<td>0.001</td>
</tr>
<tr>
<td>Cloudy, no moon, far from city lights</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

*Legal definition of dusk.*

by the plot in Fig. 3. Figure 4 shows the geometry of imaging the sun directly using the APD-FPA camera with a lens focal length \( f = 21 \text{ cm} \) and focal ratio setting \( f/# = 5.6 \), required for 100% sensitive-area-fill-factor over the full \( 1024 \times 1024 \) FPA area, as calculated in Ref. 2.

The dashed blue curve in Fig. 3 represents the calculated spectral irradiance of the solar black body obtained from Eq. (1), which is derived from the Planck black body law.

\[
F(\lambda) d\lambda = \frac{P(\lambda)}{4\pi r^2} d\lambda = \frac{2\pi\hbar c^2}{\lambda^5 \exp(\hbar c/\lambda k_B T) - 1} \left( \frac{R_{\text{sun}}^2}{r^2} \right) d\lambda \quad \text{[W/m²]}. \tag{1}
\]

In Eq. (1), the average distance of the Earth from the sun is given by \( r_{\text{sun}} = 1.472 \times 10^{11} \text{ m} \) and the radius of the sun \( R_{\text{sun}} = 6.96 \times 10^8 \text{ m} \). The G173-03 standard described in
Fig. 3 is produced by the American Society for Testing and Materials (ASTM) for photovoltaic performance evaluation and also defines in addition to AM 0 (for orbit around the Earth), two standard terrestrial solar spectral irradiance curves both at AM 1.5 conditions.

To calculate the AM 0 and AM 1.5 illuminances $E_l$, the radiometric AM 0 and AM 1.5 spectral irradiances need to be converted to photometric spectral illuminances $E_i$ [lumens/m²-nm] using the conversion formula in Eq. (2).

$$P_{\text{lumens}} = K_{\text{max}} \int_0^\infty V(\lambda) p(\lambda) d\lambda. \tag{2}$$

The photopic response curve $V(\lambda)$ of the human eye is shown in Fig. 5 and Fig. 6 shows the spectral illuminance curves for solar AM 0 and AM 1.5 conditions. In Eq. (2), $K_{\text{max}}=683$ lumens/W and $p(\lambda)$ is the radiometric spectral irradiance.

Integrating the AM 0 spectral illuminance curve in Fig. 6 over wavelengths from 280 to 4000 nm yields a value of total illuminance that closely matches the maximum value of $E_{i,\text{AM }0}=130,000$ lux in Table 1, as expected. Integrating the AM 1.5 Global Tilt and AM 1.5 Direct curves in Fig. 6 yields $E_{i,\text{AM }1.5\text{ GT}}=110,000$ lux and $E_{i,\text{AM }1.5\text{ D}}=97,000$ lux, respectively. These values represent illuminances in units of lumens/m² at the entrance aperture of a camera staring directly into the sun.

When imaging the sun directly, as shown in Fig. 4 using a $1024 \times 1024$ pixel focal plane array consisting of $27 \mu m$, wide dynamic range mesa pixels shown in Fig. 1, the photon flux incident on a pixel and the resulting photocurrent produced by the pixel can be calculated. Table 2 lists important camera parameter values for calculating the photon flux incident on the $27 \mu m$ wide dynamic range APD pixel when imaging the sun directly, as shown in Fig. 4.

Using the parameter values in Table 2, the optical power $P_{\text{opt}}$ and photon flux $\Phi$ incident on a single APD pixel in the array can be calculated for different illuminance conditions at the camera lens aperture. If the camera is orbiting Earth in space and staring directly into the sun at the AM 0 condition, the irradiance at the camera lens will be $E_{\text{lens(AM }0)}=1356$ W/m² = 0.1356 W/cm². The total optical power admitted by the lens is given by Eq. (3).

$$P_{\text{opt-total}} = E_{\text{lens}} A_{\text{aperture}}. \tag{3}$$

In Eq. (3), $A_{\text{aperture}}$ is the camera aperture area. According to Eq. (3), the total optical power admitted by the lens is calculated to be $P_{\text{opt-total}}=1.4916$ W. For the camera in Fig. 4,

![Fig. 5](image-url)  
**Fig. 5** Photopic response $V(\lambda)$ of the human eye. Peak response occurs at $\lambda_p=555$ nm.

![Fig. 4](image-url)  
**Fig. 4** Geometry of imaging the sun directly using the APD-FPA with camera focal length $F=21$ cm and $f/\#=5.6$.

![Fig. 6](image-url)  
**Fig. 6** Spectral illuminance curves for AM 0, AM 1.5 Global Tilt, and AM 1.5 Direct solar conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>$27 \mu m$</td>
</tr>
<tr>
<td>Pixel area $A_{\text{pixel}}$</td>
<td>$729 \times 10^{-6}$ cm²</td>
</tr>
<tr>
<td>Focal plane array size</td>
<td>$1024 \times 1024$</td>
</tr>
<tr>
<td>FPA side length</td>
<td>2.7648 cm</td>
</tr>
<tr>
<td>FPA area $A_{\text{FPA}}$</td>
<td>7.644 cm²</td>
</tr>
<tr>
<td>Camera lens focal length</td>
<td>21 cm</td>
</tr>
<tr>
<td>Focal ratio setting $f/#$</td>
<td>5.6</td>
</tr>
<tr>
<td>Camera entrance aperture area $A_{\text{aperture}}$</td>
<td>11.04 cm²</td>
</tr>
<tr>
<td>Area of the sun’s image projected onto the FPA $A_{\text{Sun-FPA}}$</td>
<td>0.0309 cm²</td>
</tr>
<tr>
<td>Total number of pixels that record the sun’s projected image</td>
<td>4238 pixels</td>
</tr>
</tbody>
</table>
imaging the sun directly, the angle \( \theta_{\text{sun}} = \arctan \left( \frac{R_{\text{sun}}}{r_{\text{sun}}} \right) \) = 0.0045 rad and the corresponding solid angle subtended by the sun at the camera lens is given by \( \Omega_{\text{sun}} = \pi (\theta_{\text{sun}})^2 \) sr. The total optical power \( P_{\text{opt-total}} = 1.4916 \) W, projected by the sun into \( \Omega_{\text{sun}} \) under AM 0 conditions will be focused onto the 4238 pixels on the FPA that record the sun’s projected image. The total optical power incident per pixel is therefore given by \( P_{\text{opt-pixel}} = P_{\text{opt-total}} / 4238 = 0.35 \) mW, however, not all of this incident optical power is actually detected by the mesa APD. As the sun descends toward the horizon, higher airmass conditions apply that produce less illuminance, approaching the 50,000 lux lower limit shown in Table 1.

Imaging a scene is different from direct imaging of the sun, because the scene is subtended by the field of view of the camera and the scene is projected onto the full light receiver electronics should be capable of supporting linear and Geiger-mode operation.

Fig. 7 APD photocurrent as a function of the illuminance at the camera lens aperture for a 27 \( \mu \)m mesa isolated pixel without a light focusing sapphire microlens, operating at unity internal gain \( G = 1 \). Camera lens focal length \( F = 21 \) cm with \( f/\# = 5.6 \).

### 2.2 Calculated Photocurrent Noise and Dark Current Noise of the Wide Dynamic Range Mesa Avalanche Photodiode

The photoelectron and dark current noise are contributed by the mesa APD detector to the overall noise of the pixel or optical receiver, that also includes a contribution from the electronic readout noise of the pixel control circuit. The photocurrent noise can be calculated for the two terminal mesa APD with guard diode shown in Fig. 1, with parameters \( \beta \) and \( \gamma \) describing the probability of a photogenerated electron being collected in the active part of the device and multiplied or collected by the guard diode and not multiplied, respectively. The parameters \( \beta \) and \( \gamma \) are therefore random variables. The instantaneous mesa APD photocurrent with a guard diode structure is given by Eq. (6).

\[
i_p(t) = (1 - R)(1 - \exp(- \alpha(x,y)))[\beta + \gamma \frac{G}{G} q\Phi] = qG\beta \frac{\Phi}{T_{\text{int}}} + q\gamma \frac{\Phi}{T_{\text{int}}}. \tag{6}\]

Equation (6) expresses the instantaneous APD photocurrent where \( \beta \), \( \gamma \), and \( G \) are all random variables with assumed \( \beta + \gamma = 1 \). The quantity \( R \) represents the optical power reflectance, \( \alpha(x,y) \) is the absorption coefficient of silicon, and \( h(x,y) \) is the silicon mesa height. The quantity \( m \) represents the number of photogenerated electrons produced during integration time interval \( T_{\text{int}} \) and \( G \) describes the avalanche gain. The variables \( \beta \) and \( \gamma \) represent the fractions of \( m \) that undergo gain multiplication or not, respectively. The mean photocurrent and the variance of the photocurrent for the mesa APD with a guard diode can be calculated. The instantaneous photocurrent in the APD with guard diode is composed of multiplied and unmultiplied photoelectrons and both are expressed by Eqs. (7) and (8), respectively.

\[
i_d(t) = \sum_i X_i G_j \beta h(t - l \Delta t), \tag{7}\]

\[
i_u(t) = \sum_i X_i G_j \gamma h(t - l \Delta t). \tag{8}\]

To image with high sensitivity over the normal range of illumination conditions shown in Fig. 7, the APD optical receiver electronics should be capable of supporting linear and Geiger-mode operation.
The total instantaneous photocurrent $i_p(t)$ can be written as the sum of Eqs. (7) and (8) as given by Eq. (9).

$$i_p(t) = \sum_i X_i G_i \gamma h(t - l) = \sum_i X_i \gamma h(t - l).$$  (8)

The mean value of the random variable $X_i$ is given by Eq. (10).

$$\langle X_i \rangle = \rho = T \eta_{abs} \Phi \Delta t.$$  (10)

In Eq. (10), $T$ represents the optical power transmittance into the device and $\eta_{abs}$ represents the absorption efficiency of light in the silicon. The expression for the mean photocurrent can therefore be written as shown in Eq. (11).

$$\langle i_p(t) \rangle = \sum_i \langle X_i \rangle (G_i) (\beta) h(t - l) = \langle X_i \rangle (\gamma) h(t - l).$$  (11)

Equation (11) can be solved in the limit of $\Delta t \to 0$ to yield the mean photocurrent in Eq. (12).

$$\langle i_p(t) \rangle = T \eta_{abs} \Phi (G_i) (\beta) \int_0^{\infty} h(t) \, dt + T \eta_{abs} \Phi (\gamma) \int_0^{\infty} h(t) \, dt$$  (12)

To calculate the variance of the photocurrent in the presence of random gain $G$, random $\beta$, and $\gamma$, the mean square value of the photocurrent must be calculated first according to Eq. (13) where the two currents are uncorrelated.

$$\langle i_p^2(t) \rangle = \langle i_p^2(t) \rangle + \langle i_p(t) \rangle^2.$$  (13)

Calculating the mean square value of the photocurrent yields the result in Eq. (14).

$$\langle i_p^2(t) \rangle = T^2 \eta_{abs} \Phi^2 (G) (\beta)^2 q^2 + T \eta_{abs} \Phi (G^2) (\beta^2) (2q^2)B$$  (14)

The variance of the photocurrent in the APD device with a guard diode can now be calculated according to Eq. (15) using Eqs. (12) and (14).

$$\sigma_p^2 = \langle i_p^2(t) \rangle - \langle i_p(t) \rangle^2 = 2T \eta_{abs} \Phi q^2 B (F_{cl}(G) (\beta^2) (2q^2)B$$  (15)

Since $G$, $\beta$, and $\gamma$ are random variables, a relationship between their mean square values and the square of the means can be defined using excess noise factors as formulated in Eq. (15).  The excess noise factors for $G$, $\beta$, $\gamma$, and $\beta \gamma$ are provided in Eq. (16).

$$F_G = \frac{\langle G^2 \rangle}{\langle G \rangle^2}; \quad F_\beta = \frac{\langle \beta^2 \rangle}{\langle \beta \rangle^2}; \quad F_\gamma = \frac{\langle \gamma^2 \rangle}{\langle \gamma \rangle^2}; \quad F_{\beta \gamma} = \frac{\langle \beta \gamma \rangle}{\langle \beta \rangle \langle \gamma \rangle}.$$  (16)

Equation (15) describes the photoelectron noise for the mesa APD structure shown in Fig. 1, with two terminals, a guard diode region and random gain. In Eq. (15), the mean values for $\beta$ and $\gamma$ are calculated as a function of the optical wavelength for a particular guard diode boundary function $f_{GD}(x, y)$, seen in Fig. 1. The excess noise factors associated with $\beta$, $\gamma$, and $\beta \gamma$ can be determined experimentally in a fabricated device or by Monte Carlo simulation.

In addition to the photoelectron noise contribution by the mesa APD device, the thermally generated dark current in the detector also contributes to the overall noise. The contribution to the detector dark current in the mesa APD structure of Fig. 1 with a guard diode will be composed of multiplied and unmultiplied dark current. The thermally generated dark current $i_D$ in the mesa APD device can be defined and measured under low reverse bias conditions with the APD $p/n$-junction fully depleted to the silicon-(AlN)-sapphire interface, with a peak electric field below that needed for avalanche gain in the device. According to this definition, the mean APD dark current is given by Eq. (17).

$$i_D = q \Phi \frac{\Phi_T}{T_{int}}.$$  (17)

In Eq. (17), the quantity $\Phi_T$ describes the average number of thermally generated electrons per second and $q$ is the charge of an electron. The quantity $\Phi_T$ describes the average number of dark electrons generated during integration time interval $T_{int}$. The thermally generated mean dark current $i_D$ can be calculated to yield an estimate for the reverse biased silicon mesa APD $p/n$-junction. Assuming the dark current is only generated thermally in the silicon bulk, $p < n_i$ and $n < n_i$, where $n_i$ is the silicon intrinsic carrier concentration and only a single type of trap with an energy located inside the bandgap participates; then the recombination rate $U$ is described by Eq. (18).

$$U = -n_i \left[ \frac{\sigma_p \sigma_r v_{TH} T_{int}}{\exp \left( E_F - E_i \right) kT} + \sigma_p \exp \left( E_F - E_i \right) kT \right].$$  (18)

In Eq. (18), the quantities $\sigma_p$ and $\sigma_r$ represent the electron and hole capture cross section probabilities, $v_{TH}$ is the carrier thermal velocity, $N_T$ is the trap density, $E_F$ is the trap energy level, $E_i$ is the intrinsic Fermi level, and $n_i$ is the intrinsic carrier density. Many of the quantities in Eq. (18) depend on temperature as does the recombination rate itself. The thermally generated dark current density from the silicon bulk is calculated by integrating Eq. (18) over the full width $W$ of the reverse biased mesa APD $p/n$-junction depletion region, as given by Eq. (19).

$$J_{gen} = \left. \int_0^W q |U| dx = q U |W = q n_i W \right| \tau_n.$$  (19)

In Eq. (19), the quantity $\tau_n$ represents the mean electron life time in $p$-type silicon material. An estimate of the mean
APD dark current from Eq. (19) is obtained by multiplying the result by the cross sectional area $A_{APD}$ of the mesa APD device to yield Eq. (20).

$$\langle i_{D,\text{estimated}} \rangle = \frac{q n_{e} A_{APD} W}{\tau_{n}}; \quad \tau_{n} = \frac{1}{\sigma_{n} v_{Th} p N_{T}}.$$  (20)

The quantity $\tau_{n}$ in Eq. (20), depends on the electron capture cross section, carrier thermal velocity, and on the trap concentration. High values for $\tau_{n}$ in a silicon $p/n$-junction can reach 100 $\mu$s.\textsuperscript{21,22} Equation (20) assumes that the dark current arises from the silicon bulk and that surface generated dark current contribution to the total dark current is zero. This approximation is valid for well passivated mesa sidewalls. The formalism presented here describes the probabilities for dark electrons to be collected by the active mesa APD versus the guard diode and allows sufficient flexibility for the inclusion of the surface generated dark current contribution if needed.

When the reverse bias voltage on the APD is increased to the level of avalanche gain onset, a fraction of $\Phi_{e}$ will be multiplied and the instantaneous dark current in the APD will be described by the sum of multiplied dark electrons collected in the active silicon and unmultipled dark electrons collected in the guard diode as given by Eq. (21).

$$i_{D}(t) = i_{D_{a}}(t) + i_{D_{g}}(t),$$

$$i_{D_{a}}(t) = \sum_{l} X_{l} \eta_{a} G_{l} h(t - \Delta t),$$

$$i_{D_{g}}(t) = \sum_{l} X_{l} \eta_{g} h(t - \Delta t).$$  (21)

In Eq. (21), the quantities $\eta_{a}$, $\eta_{g}$, and $G_{l}$ are random variables with random values for each collection event. The quantity $\eta_{a}$ describes the probability of a thermally generated electron being collected in the active region and therefore being multiplied in the APD, while $\eta_{g}$ describes the probability of a thermally generated electron being collected by the guard diode and therefore not being multiplied. The values $G_{l}$ represent random variables of the gain imparted to a thermal electron generated during the time interval $l$.

The random variable $X_{l}$ is described by Eq. (22).

$$X_{l} = \begin{cases} 0 & \text{if } 1-p \\ 1 & \text{if } p \end{cases}.$$  (22)

The probability $p = \Phi_{e} \Delta t$ represents the probability of generation of a thermal electron during the time interval $\Delta t$. It is assumed as before that the variables $\{X_{l}\}$ are independent and the variables $\{G_{l}\}$ are also independent. The mean dark current can now be expressed using Eqs. (21) and (22) according to Eq. (23).

$$\langle i_{D} \rangle = \sum_{l} \langle X_{l} \rangle \langle \eta_{a} \rangle \langle G_{l} \rangle h(t - \Delta t) + \sum_{l} \langle X_{l} \rangle \langle \eta_{g} \rangle h(t - \Delta t)$$

$$= \Phi_{e} \langle \eta_{a} \rangle \langle G_{l} \rangle \sum_{l} h(t - \Delta t) \Delta t + \Phi_{e} \langle \eta_{g} \rangle \sum_{l} h(t - \Delta t) \Delta t.$$  (23)

Taking the limit $\Delta t \to 0$, the sums in Eq. (23) become integrals according to Eq. (24).

$$\lim_{\Delta t \to 0} \sum_{l} h(t - \Delta t) = \int_{0}^{\infty} h(t) dt = q.$$  (24)

The mean dark current can now be expressed according to Eq. (25).

$$\langle i_{D} \rangle = \Phi_{e} \langle \eta_{a} \rangle \langle G_{l} \rangle q + \Phi_{e} \langle \eta_{g} \rangle q$$

$$= \Phi_{e} q((\langle \eta_{a} \rangle \langle G_{l} \rangle + \langle \eta_{g} \rangle)).$$  (25)

To calculate the dark current variance, the mean square dark current is calculated to yield the result in Eq. (26).

$$\langle i_{D}^{2} \rangle = \Phi_{e}^{2} q^{2} G_{l}^{2} \langle \eta_{a} \rangle^{2} q^{2} + \Phi_{e}^{2} q^{2} G_{l}^{2} \langle \eta_{g} \rangle^{2} q^{2}$$

$$\text{Var}(i_{D}) = \Phi_{e}^{2} q^{2} G_{l}^{2} \langle \eta_{a} \rangle^{2} = \Phi_{e}^{2} q^{2} G_{l}^{2} \langle \eta_{g} \rangle^{2}.$$  (26)

The variance of the dark current is given using Eqs. (25) and (26) according to Eq. (27).

$$\sigma_{i_{D}}^{2} = 2 \Phi_{e} q^{2} B_{G} F_{G} \langle \eta_{a} \rangle \langle G_{l} \rangle^{2} + 2 \Phi_{e} q^{2} \langle \eta_{g} \rangle F_{G} \langle \eta_{g} \rangle.$$  (27)

Since $\eta_{a}$ and $\eta_{g}$ are random variables, a relationship between their mean square values and the square of the means is defined using excess noise factors. The excess noise factors for $G$, $\eta_{a}$, $\eta_{g}$, and $\eta_{a} \eta_{g}$ are given in Eq. (28).

$$F_{G} = \frac{G_{l}^{2}}{\langle G_{l} \rangle^{2}}; \quad F_{a} = \frac{\langle \eta_{a}^{2} \rangle}{\langle \eta_{a} \rangle^{2}}; \quad F_{g} = \frac{\langle \eta_{g}^{2} \rangle}{\langle \eta_{g} \rangle^{2}}; \quad F_{ag} = \frac{\langle \eta_{a} \eta_{g} \rangle}{\langle \eta_{a} \rangle \langle \eta_{g} \rangle}.$$  (28)

Equation (27) describes the dark current noise for the mesa APD pixel design in Fig. 1 with two terminals, a guard diode region and random gain. In Eq. (27), estimates for the mean values of $\eta_{a}$ and $\eta_{g}$ can be made by assuming that $\Phi_{e}$ has a contribution only from the thermally generated bulk dark current. The thermally generated electron flux $\Phi_{e}$ is calculated from Eqs. (20) and (17) and depends on the temperature. For the case of zero surface dark current, $\langle \eta_{a} \rangle$ represents the fractional volume of active silicon to the total device mesa silicon volume and $\langle \eta_{g} \rangle$ represents the fractional volume of guard diode silicon to the total mesa silicon volume. The pyramidal mesa frustum volume is given by Eq. (29).
In Eq. (29), $A_1$ is the pyramidal frustum base area and $A_2$ is the pyramidal frustum top area. For the 27 μm pixel mesa of height $h = 10$ μm, with a guard diode boundary defined by parameter $i_{GD}=1$ μm with the same slope as the mesa sidewall as shown in Fig. 1, the mean fractional volume of the active and guard silicon is given by Eq. (30).

$$\langle \eta_a \rangle = \frac{V_{\text{active}}}{V_{\text{frustum}}} = 0.817,$$

$$\langle \eta_g \rangle = \frac{V_{\text{guard}}}{V_{\text{frustum}}} = 0.183.$$

It is assumed for the calculation of the 27 μm mesa APD pixel that the boundaries between the guard diode region and active region in the device are defined by the fixed boundary in Fig. 1, for which case the excess noise factors $F_a$ and $F_g$ in Eq. (28) are reduced to unity.

### 3 Pixel Circuit Design

The pixel sensitivity depends on the electronic readout circuit design which must be capable of controlling linear and Geiger-mode operation of the detector as shown in Fig. 7, to image successfully over the full range of natural illumination conditions. The pixel readout circuit in Fig. 8, based on a voltage source follower amplifier, may be used to control linear mode operation of the mesa APD and the circuit in Fig. 9 to control Geiger-mode operation.

The linear mode electronic readout circuit for the APD in Fig. 8 combines a voltage source follower amplifier consisting of transistor M1 and load resistor $R_L$, with pass transistor M3 to store the charge integrated at the gate capacitance of M1. The circuit is shown in the figure to be capable of performing correlated double sampling (CDS) using a second matching voltage source follower amplifier made up of transistor M2 with its own identical load resistor $R_L$ and pass transistor M4. The readout circuit in Fig. 9 implements active quenching for the Geiger-mode APD to shorten the detector reset time. During a normal image acquisition cycle, the APD and readout circuit are first reset by turning on then off reset transistor M2. Transistor M1 is then used to precharge the APD and the gate capacitance of M3 to the $V_{bias}$ dc supply voltage. In response to just a single detected photon, the large avalanche gain in the APD ($G > 10^5$) produces a photocurrent capable of quickly discharging the self-capacitance of the APD. The capacitance at the gate of M3 is also discharged by the APD photocurrent, thereby turning on M3. The transistor M3 senses the onset of the avalanche in the APD and turns on M4 which diverts a significant fraction of the charge to ground instead of it flowing through the APD junction where it can fill traps and lengthen the quench time of the detector following a detection event. An advantage of the circuits in Figs. 8 and 9 includes being able to combine them into a single compact pixel readout circuit that is capable of controlling both linear and Geiger-mode operation for the wide dynamic range mesa APD detector as shown in Fig. 10.

The circuit in Fig. 10 combines the analog APD readout circuit shown on the right with a digital readout circuit shown on the left. When the APD is biased in linear mode, transistor M7 is turned off and the APD is controlled by the analog circuit on the right. When the APD is biased in Geiger-mode, transistors M3 and M4 are turned off and M7 is turned on, allowing the APD to be controlled by the digital circuit on the left.
3.1 Linear Mode Circuit Characteristics

During a normal image frame acquisition by the linear circuit, both pass transistors M3 and M4 are initially conducting or turned on. Transistor M6 resets the APD as indicated in the pixel control clocking waveforms. Transistor M5 is used to precharge the APD self-capacitance and the gate capacitance of M1 and M2 to the $V_{CC}$ supply voltage. Transistor M4 is allowed to stay turned on briefly after M5 is turned off to allow the voltages at the gates of M1 and M2 to equalize. Following the voltage equalization, M4 is turned off, marking the start of the frame integration time $t_{int}$, indicated in Fig. 8. During the integration time a photocurrent $I_{ph}$ produced by incident illumination on the APD, discharges the precharged self-capacitance of the APD as well as the integration capacitance at the gate of transistor M1. At the end of the charge integration, pass transistor M3 is turned off and the charge is stored on the integration capacitor at the gate terminal of M1 which also serves as the input to the voltage source follower amplifier. Following the image frame integration time, the analog voltage output from the pixel circuit can be digitized using an A/D converter located on the periphery of the pixel array. The linear mode control circuit in Fig. 8 can provide low noise using CDS.

In contrast to the digital readout circuit that contributes zero electronic readout noise, the analog circuit composed of the voltage source follower and pass transistor with integration capacitor at the input of the voltage source follower, contributes to the electronic noise. Correlated double sampling shown in Fig. 10 can be used to reduce the noise contribution from the integration capacitor, however, such CDS circuitry may increase the area footprint required for the dual mode readout circuit in Fig. 10, beyond the $27 \times 27 \, \mu m^2$ limit. Therefore, it is more appropriate in the noise analysis to consider the readout circuit for linear mode operation without CDS. Such an analysis is also more conservative because it assumes the worst case noise contribution from the circuit. Figure 11 shows the linear mode readout circuit without CDS used in the signal-to-noise ratio analysis of the APD pixel.

The circuit in Fig. 11 is designed for implementation using the TSMC 0.25 $\mu m$ RF-CMOS process. M1 is biased into the constant current region after the linear capacitor $C_{g,M1}$ is precharged. Analog APD readout circuit is shown without CDS.

![Fig. 11 APD pixel readout circuit is designed using the TSMC 0.25 $\mu m$ RF-CMOS process. M1 is biased into the constant current region after the linear capacitor $C_{g,M1}$ is precharged. Analog APD readout circuit is shown without CDS.](https://www.spiedigitallibrary.org/journals/Journal-of-Electronic-Imaging/article-Digital-ARM-Analog-Presetage-APD-Pixel-Readout-Circuit/19/2/021102-9/10.1117/1.3647399)

<table>
<thead>
<tr>
<th>Table 3 Linear mode electronic readout circuit parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>$C_{g,M1}$</td>
</tr>
<tr>
<td>$M1$ gate length</td>
</tr>
<tr>
<td>$M1$ gate width</td>
</tr>
<tr>
<td>Threshold voltage</td>
</tr>
<tr>
<td>Gate oxide thickness</td>
</tr>
<tr>
<td>Load resistor $R_L$</td>
</tr>
<tr>
<td>Integration capacitor $C_{g,M1}$</td>
</tr>
</tbody>
</table>

The input voltage $V_{IN}$ at the gate of M1 is given by the initial charge $Q_{g,M1}$ deposited on the integration capacitor $C_{g,M1}$ corresponding to the precharge voltage $V_{CC}$ minus the charge that was sourced by the photocurrent flowing through the APD during the integration time interval given by Eq. (33).

$$V_{IN} = V_{CC} - \frac{(i_p)T_{int}}{C_{g,M1}}.$$  

(33)

The voltage transfer characteristic of the source follower amplifier in Fig. 11 can be calculated by knowing that M1 operates in the active region. If the integration capacitor $C_{g,M1}$ is precharged to a voltage $V_{IN} = 4.5 \, V$ as described in Eq. (32), the voltage transfer characteristic for the amplifier output voltage $V_{OUT}$ as a function of $V_{IN}$ can be calculated from Eq. (34) where $V_{TN}$ is calculated iteratively taking into consideration the body effect.
The resistance to the sample and hold output shown in Fig. 14.

Fig. 14 is contributed at the gate of MOSFET M1 and this

and can be added to yield total output noise current.

The voltage transfer characteristic of the voltage source fol-

The resistor

and since

gs 1, as shown in Fig. 13. Since the three resistances

1, and 1 gs 1 in Fig. 13 represents the finite output

1, and since

Ron 1, and 1 gs 1, then the noise due to the

1, then the noise due to the

noise of the sample and hold output shown in Fig. 14.

- sample and hold

Sample and hold circuit of the source follower amplifier of

Fig. 14

Fig. 13

The noise source from the linear mode circuit in Fig. 11

is obtained by analyzing the small signal noise models.

The electronic noise result from Eq. 35 is used in the

sensitivity analysis of Sec. 4 for the wide dynamic range

mesa APD optical receiver based on the 27 μm mesa APD

of Fig. 1.

4 Sensitivity of the Linear and Geiger-Mode

Avalanche Photodiode Optical Receiver

The sensitivity or signal-to-noise of the wide dynamic range mesa APD optical receiver is calculated using the

mean photocurrent given in Eq. (4), together with the vari-

ance of the photocurrent in Eq. (15), the dark current in Eq.

(27) and the electronic circuit readout noise in Eq. (36)

according to Eq. (37).

\[
\text{SNR}_{\text{APD-linear-mode-receiver}} = \frac{(I_p(t))^2}{\sigma_I^2 + \sigma_D^2 + \sigma_{en}^2}.
\]

Other sources of noise such as the background noise

which is a type of photon noise associated with light from

extraneous optical sources other than the signal of interest,

is not considered in the analysis. Background noise is

mainly a problem when imaging at midwave IR and long-

wave IR wavelengths where objects in a scene emit radia-

tion according to the Planck black body law.\ref{17} Leakage

currents are also not considered in the noise analysis

because the surface leakage currents usually occur at poorly

passivated surfaces of semiconductor p/n-junctions, for ex-

ample, when ions on the semiconductor surface induce mir-

ror charges in the semiconductor that form surface chan-

nels, enabling a surface leakage current to flow.\ref{30} Bulk

leakage currents may occur as a result of defects in the

crystal structure of the bulk semiconductor material. In the

mesa structure APD design presented here, the surfaces of

the mesa are passivated with thermally grown silicon diox-

ide on the (100) and (111) planes. Therefore, it is expected

that surface leakage currents at the APD p/n-junction will

be minimized through good quality thermally grown oxide

passivation. Surface leakage currents at the (111) mesa

sidewalls of the APD are expected to be negligible com-

pared to the bulk dark current in the device. The APD guard
Table 4  Sensitivity calculation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>APD focal plane array temperature</td>
<td>$T = 243$ K (two-stage thermoelectric cooler)</td>
</tr>
<tr>
<td>APD array size</td>
<td>1024 × 1024 pixels</td>
</tr>
<tr>
<td>APD pixel size</td>
<td>$a = 27$ $\mu$m</td>
</tr>
<tr>
<td>APD mesa pixel height</td>
<td>$h = 10$ $\mu$m</td>
</tr>
<tr>
<td>Microlens</td>
<td>No microlens</td>
</tr>
<tr>
<td>Camera lens focal length</td>
<td>$F = 21$ cm</td>
</tr>
<tr>
<td>Camera focal ratio</td>
<td>$f/# = 5.6$</td>
</tr>
<tr>
<td>Minority carrier lifetime in APD silicon</td>
<td>$\tau_n = 100$ $\mu$s$^{-2}$</td>
</tr>
<tr>
<td>APD ionization ratio</td>
<td>$k_{e,h} = 0.2$ used to calculate $F_G$ after McIntyre</td>
</tr>
<tr>
<td>Transconductance of M1</td>
<td>$g_{m1} = 0.85 \times 10^{-3}$ A/V</td>
</tr>
<tr>
<td>Load resistor $R_L$</td>
<td>$R_L = 10$ k$\Omega$</td>
</tr>
<tr>
<td>Integration capacitor $C_{pM1}$</td>
<td>$C_{pM1} = 401.43$ fF</td>
</tr>
<tr>
<td>APD integration time $T_{int}$</td>
<td>$T_{int} = 1/2B$</td>
</tr>
</tbody>
</table>

diode at the device periphery will also collect and limit the multiplication of any surface leakage currents.19

The signal-to-noise ratio is calculated for the linear mode 27 $\mu$m mesa APD pixel according to Eq. (37) for the normal range of illumination conditions with the following assumptions listed in Table 4. Using the parameter values listed in Table 4, the signal-to-noise ratio for the wide dynamic range APD optical receiver in linear mode is calculated according to Eq. (37) for different natural illumination conditions. The results are shown in Figs. 15–21 for AM 0 to late dusk.

In Fig. 15 the APD stares into the sun and unity gain provides SNR above the unity threshold. The maximum integration time $T_{int-max} = 17.6$ ns is also indicated due to the large APD photocurrent that quickly discharges the integration capacitor of the linear readout circuit.

In Fig. 16 the maximum integration $T_{int-max} = 25.7$ ns is indicated because of the large APD photocurrent that quickly discharges the integration capacitor of the linear readout circuit.

In Fig. 17, gain >3 becomes necessary to provide larger than unity signal-to-noise ratio.

In Fig. 18, gain >30 becomes necessary to provide larger than unity signal-to-noise ratio.

In Fig. 19, gain >200 becomes necessary to provide larger than unity signal-to-noise ratio.

In Fig. 20, gain >5000 becomes necessary to provide larger than unity signal-to-noise ratio.

In Fig. 21, gain >50,000 becomes necessary to provide larger than unity signal-to-noise ratio. At late dusk, the capability of the linear mode imager to provide high sensitiv-
ity for imaging becomes limited, especially at larger bandwidths. After late dusk, however, the Geiger-mode operation of the 27 μm mesa APD detector without a microlens is supported as calculated in Fig. 7.

The signal-to-noise ratio for the Geiger-mode mesa APD optical receiver that uses the APD in Fig. 1 and the electronic readout circuit in Fig. 10 is calculated using the expression given by Eq. (38).

\[
\text{SNR}_{\text{APD-Geiger-mode-receiver}} = \frac{(i_p(t))^2}{\sigma_p^2 + \sigma_D^2}.
\]  

In Eq. (38), the digital pixel control circuit does not add to the optical receiver noise.\(^{24,25}\) This enabling characteristic of the Geiger-mode pixel control circuit allows the optical receiver to operate with high sensitivity at the low light levels indicated in Fig. 7. Using the parameter values listed in Table 4, without the entries for the linear circuit, the signal-to-noise ratio for the wide dynamic range APD optical receiver in Geiger-mode is calculated according to Eq. (38). The results are shown in Figs. 22–26 for late dusk to a cloudy night with no moon.

In Fig. 22, the 27 μm mesa APD pixel is shown to provide high sensitivity in the Geiger-mode. The Geiger-mode APD has 8-bit resolution and a quench time of 50 ns.

Fig. 19 SNR of the linear mode APD imager before dusk with 200 lux illumination. Bandwidths of 1 × 10^4 Hz (thin solid line) and 1 × 10^9 Hz (dashed line) are shown.

Fig. 20 SNR of the linear mode APD imager at dusk with 10 lux illumination. Bandwidths of 1 × 10^4 Hz (thin solid line) and 1 × 10^9 Hz (dashed line) are shown.

Fig. 21 SNR of the linear mode APD imager at late dusk with 1 lux illumination. Bandwidths of 1 × 10^4 Hz (thin solid line) and 1 × 10^9 Hz (dashed line) are shown.

Fig. 22 SNR of the Geiger-mode APD imager at late dusk with 1 lux illumination. The Geiger-mode APD has 8-bit resolution and a quench time of 50 ns.

Fig. 23 SNR of the Geiger-mode APD imager on a clear night with full moon and 0.1 lux illumination. The Geiger-mode APD has 8-bit resolution and quench time of 50 ns.
In Fig. 23, the SNR for $T_{\text{int}} = 200 \text{ ms}$ and with 8-bit resolution is $750$ with $50 \text{ frames/sec}$. In Fig. 24, the SNR for $T_{\text{int}} = 2.25 \text{ ms}$ and with 8-bit resolution is $1 \times 10^4$ with $220 \text{ frames/sec}$. In Fig. 25, the SNR for $T_{\text{int}} = 10 \text{ msec}$ and with 8-bit resolution is $750$ with $50 \text{ frames/sec}$. In Fig. 26, the SNR for $T_{\text{int}} = 10 \text{ msec}$ and with 8-bit resolution is $7$ with $50 \text{ frames/sec}$. The calculations of signal-to-noise ratio for the $27 \mu \text{m}$ wide dynamic range mesa APD optical receiver operating in Geiger-mode show that the imager will be capable of recording an image even under the lowest natural illumination conditions in Fig. 26. This result is important because it confirms that the detector array design should be capable of imaging successfully under the broadest range of natural illuminations when cooled only to $-30^\circ \text{C}$ using a compact two-stage thermoelectric cooler.

5 Concluding Remarks

It is shown in this detailed design study that a novel back-illuminated silicon APD array architecture using (100) epitaxial silicon grown on $R$-plane sapphire having a lattice-matched AlN antireflective layer provides a unique means for creating high sensitivity, wide dynamic range APD device arrays for large area, high resolution, solid-state APD-FPA imagers with zero optical crosstalk and 100% sensitive-area-fill-factor. Such APD-FPA imagers could be used for both passive and active 2-D and 3-D imaging applications. The detailed calculations and analysis presented here show that the APD-FPA imager design will be capable of operating with high signal-to-noise ratio over the full range of natural illumination conditions near room temperature. Such a camera represents a novel, enabling technology for scientific and industrial applications.

References


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