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Authors

Finkelstein, Hod
Gross, Matthias
Lo, Yu-Hwa
et al.

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Analysis of Hot-Carrier Luminescence for Infrared Single-Photon Upconversion and Readout

Hod Finkelstein, *Student Member, IEEE*, Matthias Gross, Yu-Hwa Lo, and Sadik Esener, *Fellow, IEEE*

Abstract—We propose and analyze a new method for single-photon wavelength up-conversion using optical coupling between a primary infrared (IR) single-photon avalanche diode (SPAD) and a complementary metal oxide semiconductor (CMOS) silicon SPAD, which are fused through a silicon dioxide passivation layer. A primary IR photon induces an avalanche in the IR SPAD. The photons produced by hot-carrier recombination are subsequently sensed by the silicon SPAD, thus, allowing for on-die data processing. Because the devices are fused through their passivation layers, lattice mismatch issues between the semiconductor materials are avoided. We develop a model for calculating the conversion efficiency of the device, and use realistic device parameters to estimate up to 97% upconversion efficiency and 33% system efficiency, limited by the IR detector alone. The new scheme offers a low-cost means to manufacture dense IR-SPAD arrays, while significantly reducing their afterpulsing. We show that this high-speed compact method for upconverting IR photons is feasible and efficient.

Index Terms—Avalanche photodiodes, single photon detectors, wavelength upconversion.

I. INTRODUCTION

SINGLE-PHOTON detection at infrared wavelengths has gained relevance in recent years due to its central role in quantum communications [1], eye-safe laser detection and ranging (LIDAR) [2], optical time-domain reflectometry (OTDR) [3], and in semiconductor failure analysis [4]. IR single-photon detectors should ideally operate at high frequencies (tens to hundreds of megahertz), consume minimal power (<1 nW/bit), operate reliably at noncryogenic temperatures over many cycles, and be manufacturable at a low cost. When operated in arrays, such devices should also have a small pitch and low pixel-to-pixel crosstalk.

Several figures of merit are used to evaluate single-photon detectors. The *single-photon detection probability* η is the product of the probabilities of a photon being absorbed in the material and of it initiating a detectable avalanche. The device's *spectral response* describes the wavelength dependence of this detection probability. These metrics depend on the percentage of pixel area, which collect photons (fill ratio); on the absorbing layer's composition, depth and thickness; and on the electric field distribution in the multiplication region, as will be detailed in Section III.

During the recharge process following an avalanche, the SPAD is temporarily biased below the breakdown voltage, and

cannot generate an avalanche pulse in response to a photon. This time is called the *device dead time* and depends on the recharge mechanism, on the overbias above breakdown, and most significantly, on the junction's capacitance.

Dark counts result from avalanches, which are not induced by absorbed photons. They can originate from thermally generated carriers; from band-to-band tunneling; via trap-assisted tunneling; and by afterpulsing—the release of carriers trapped in prior avalanches. The latter mechanism is an important factor in determining the device dead time.

The time-delay spread between the photon absorption event and the clocking of the resulting electrical signal depends on the diameter of the SPAD as well as on the timing circuitry. It determines the *timing resolution* of the single-photon detector.

Other factors such as active area, pixel pitch, and manufacturing cost are also important in the evaluation of single-photon detectors.

Visible-wavelength single-photon detection has been extensively investigated. Silicon SPADs have recently been demonstrated on commercial deep submicron technologies, allowing for compact pixels with 25% fill factor, with less than 5 ns of dead time and with digital outputs [5]. Such devices can be integrated into arrays with the quenching, recharge, and processing circuitry on the same die.

Various techniques have been employed for single-photon detection in the IR. Superconducting transition-edge sensors detect the subtle temperature change in small-volume tungsten microcalorimeters in response to the absorption of a photon [6]. These devices offer excellent timing accuracy, a very low dark current, and no afterpulsing. However, they are limited by their microsecond recovery time, their dark count rate is excessive, and they require cooling to 4.2 K. In addition, they also require very-low-noise amplifiers, which must also be cooled. Superconducting niobium [7] and niobium-nitride [8] nanowires have also been used for single-photon detection, achieving gigahertz operation, but still requiring cryogenic cooling. Furthermore, production of such devices is expensive, and has not been demonstrated in large arrays or in mass scale.

Solid-state IR SPADs have been demonstrated using a planar geometry and a standard semiconductor processing flow [9]. These detectors traditionally have separate absorption and multiplication regions, whereby, for example, photons are absorbed in a thick (several microns) lightly doped InGaAs layer. The photo-generated carriers are swept towards an InP high-field multiplication region where impact ionizations provide gain. When the extraction rate of carriers from this multiplication region falls below the creation rate, an avalanche breakdown is said to occur and the gain becomes “infinite.” In this mode, known as Geiger mode (GM), single-photon detection becomes

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The authors are with the Department of Electrical and Computer Engineering, University of California-San Diego, San Diego, CA 92093 USA (e-mail: hfinkels@ucsd.edu; mgross@ece.ucsd.edu; ylo@ece.ucsd.edu; sadik@ece.ucsd.edu).

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possible. The avalanche must be quenched to avoid damage to the junction.

Quenching can be achieved either passively by using a voltage-limiting resistor in series with the device, or actively by using a circuit that senses the onset of the avalanche, and subsequently quenches it. Once the avalanche has been quenched, the diode capacitance must be recharged—either passively, through the quenching resistor; or actively, using a recharging circuit.

A new type of quenching mechanism has been demonstrated by Golovin *et al.* [10], whereby, a resistive layer is deposited on top of the p-n junction. When an avalanche occurs, charges accumulate on the interface between this resistive layer and the silicon, thereby, creating a negative feedback loop that quickly quenches the avalanche. One of the main benefits of this scheme is that it integrates the quenching function into the device. This can have important benefits to devices manufactured in non-commercial or nonsilicon processes, where resistors are not available.

IR Geiger-mode single-photon avalanche diodes (GM-SPADs) have been shown to have detection probabilities of the order of 33% when operated 5% above their breakdown voltage [11]. They are amenable to integration in large arrays and to mass production because they can be manufactured using standard lithographically defined processing techniques. However, the support circuitry, including the quenching, recharging, and processing circuitry must be implemented externally, usually in silicon [12]. Recently, one of the authors demonstrated an InP/InGaAs metal–oxide–semiconductor (MOS) SPAD, which (similarly to [10]) integrates the quenching function into the device [13]. We expect this to significantly reduce the junction capacitance, and consequently, the recharging time and power dissipation.

The main deficiency of GM-SPADs lies in their excessive noise, which originates from four sources [14]. Hole-electron pairs, thermally generated at the edge of the high field region through Shockley–Read–Hall generation and separated by the strong electric field, can cause a “false” avalanche [15]. Trap-assisted tunneling depends on the defect density in addition to the doping, and may be exacerbated at high electric fields by barrier lowering via the Poole–Frenkel effect [14]–[16]. Direct band-to-band tunneling requires strong electric fields above 7×10^5 V/cm, and occurs in devices with a breakdown voltage lower than $4E_G/q$, where E_G is the bandgap energy and q is the electron charge [15], [16]. Finally, afterpulsing which results from the release of deep traps trapped during previous SPAD cycles, increases with high defect densities, and is linearly dependent on the total charge flowing during an avalanche [14]. The rate of emission of deep traps follows an exponentially decaying distribution, which depends on the activation energy of each deep trap mechanism.

Whereas the first three mechanisms can be reduced by cooling the device, deep trap lifetimes increase exponentially as temperature is decreased. Because thermal generation and tunneling increase as the bandgap decreases, it is necessary to cool IR SPAD, usually to about 200 K. At these temperatures, afterpulsing becomes the dominant noise source with rates in the order of tens of kilohertz, and it becomes the main bottleneck for

device bandwidth [9]–[17]. Time gating can reduce the effect of afterpulsing [11]–[18], but due to its exponential time distribution, the separation between gates (device dead time) must be made long enough compared with the afterpulse lifetime, in order to sufficiently reduce the probability of experiencing an afterpulse during an exposure time gate. Furthermore, time gating is only possible when the arrival time of the photon is known to be within the duration of the gate. At low temperatures, SPADs can still be operated in free-running mode with minimal afterpulsing effects, but only if a sufficiently long hold-off time is ensured following an avalanche, thereby, severely limiting the detection rate [19].

For a given technology, afterpulsing can be reduced by limiting the charge flowing during an avalanche. This may be done by active quenching but is achieved more efficiently by reducing the junction capacitance. The capacitance in IR SPADs is dominated by the capacitances of the readout, recharge, and quenching circuitry, because these operations are implemented off-chip, either on a board or on a silicon die. Connections are made either by wire bonding [9] or by using indium bumps [20]. This limits the pixel pitch, and may result in capacitances of the order of picofarads, thus, deteriorating the noise performance of the device due to afterpulsing.

Recently, a scheme was described for integrating the various SPAD components using three-wafer direct bonding with crossvias [21]. While this technique holds much promise for reducing the junction node's capacitance, it requires complex and expensive processing, and has yet to be demonstrated for large arrays.

Another recent report demonstrated sum-frequency generation using a periodically poled lithium-niobate waveguide coupled to a low-jitter silicon SPAD as a means of reducing afterpulsing and jitter in IR single-photon detection [22]. A continuous wave laser is used to seed the nonlinear conversion. Dark counts are suppressed thanks to the superior performance of silicon SPADs. Optimal performance has been achieved with a pump power of approximately 300 mW and an overall conversion efficiency of 5%–7%. Because the scheme is targeted at quantum key distribution, only single-detector upconversion has been studied. Power-sensitive applications including IR SPAD arrays will benefit from a more power-efficient scheme.

In this paper, we propose and model a new interconnection and readout scheme, which does not require any electrical interconnection between the IR SPAD and the complementary MOS (CMOS) readout circuitry, offers superior upconversion efficiencies with low power, and is scalable to large arrays. By bypassing the requirement of electrical bonding between the SPAD pixels and the readout circuitry, the capacitance seen by the junction is significantly reduced. As discussed earlier, this results in a reduction in afterpulsing, which is the dominant noise source at low temperatures, while simultaneously decreasing the device dead time. The proposed method also promises to greatly simplify the manufacturing of integrated IR-SPAD devices and to improve their fill factor.

The proposed scheme is based on wavelength upconversion using a byproduct of the avalanche process, namely hot-carrier luminescence from the multiplication layer of the device. This

Fig. 1. InP energy band diagram illustrating hot-carrier luminescence in a direct recombination processes. A hot electron accelerated by the strong electric field recombines with a hole at the valence band. The excess energy is released in the form of a photon with energy $\hbar\omega > E_{gd}$. A low-energy infrared component due to transitions between the light and heavy hole bands is also observed.

luminescence is shown to have a significant component at higher energies than the bandgap of the absorbing material, and can therefore be extended to many IR detection materials. Readout of the luminescent photons is achieved by a coupled silicon single-photon avalanche diode.

One of the main advantages of the proposed device lies in its simple manufacturing flow. Heterogeneous integration severely limits the combinations of materials, which can be directly interfaced. Moreover, electrical connections from III-V devices require additional masking layers, and reduce the pixel pitch to tens of microns [20], which is unacceptably high for large arrays. Here, we propose to utilize a mature wafer-level glass-to-glass fusing technology [21] in order to connect between a III-V SPAD, which detects the primary IR photon and a silicon CMOS SPAD, which detects the up-converted photons and which processes the information on the same die.

Section II of this paper reviews the physics of hot-carrier luminescence in avalanche photodiodes. Section III describes the model of the optical readout and derives an expression for the upconversion efficiency as well as the power consumption per avalanche. Section IV provides a numerical calculation of upconversion efficiency and power consumption, and compares the proposed scheme's performance with traditional readout setups.

II. HOT-CARRIER LUMINESCENCE IN AVALANCHE PHOTODIODES

A. Physics of Hot-Carrier Luminescence

Hot-carrier luminescence has been extensively studied since the 1950s [23], [24]. It is believed to be the primary mechanism responsible for avalanche spreading [25], and has traditionally been viewed as a detrimental side product of the avalanche, resulting in optical crosstalk [14] and a potential source for eavesdropping in quantum communications channels [26]. Hot-carrier luminescence in MOSFET channels has also been widely used to investigate defects in switching integrated circuits [4].

Hot-carrier luminescence most likely results from recombination of hot electrons with holes (Fig. 1) [27], [28]. In direct

Fig. 2. Calculated spectrum of electroluminescent photons emitted at the junction of an InP p-n junction.

bandgap materials, a photon is emitted whose energy equals the difference between the hot electron's initial energy and the bandgap. In an indirect recombination process, both energy and momentum must be exchanged, and the probability of such events is considerably lower, depending on the availability of suitable phonons. This is manifested by the different electron temperatures in these processes. In GaAs, the direct recombination process is characterized by an electron temperature of 800 K while the indirect process in the same material exhibits a temperature of 3000 K [28]. The higher temperature stems from a longer mean lifetime, consistent with a less probable recombination event.

For a direct bandgap material, such as GaAs or InP, the photon emission rate is given by

$$R_d(\hbar\omega) \propto \hbar\omega(\hbar\omega - E_{gd})^{1/2} f(E)[1 - f(E - \hbar\omega)] \quad (1)$$

where $\hbar\omega$ is the emitted photons' energy, E_{gd} is the direct bandgap, E is the electron energy above the bottom of the conduction band, $f(E)$ and $[1 - f(E - \hbar\omega)]$ are the hot electron and the hole distributions, respectively, both of which strongly depend on the hot-carrier temperature [28]. The emission spectrum of InP was calculated using (1), and is shown in Fig. 2. Because the photons carry the excess energy after the recombination, $\hbar\omega \geq E_{gd}$, thereby, achieving energy upconversion.

The efficiency of this upconversion strongly depends on the electroluminescence yield, i.e., the photon emission rate per unit avalanche charge. This figure is quite difficult to measure due to self-absorption by the emitting device, the detector's spectral response, the effect of defects, and collection uncertainties due to reflections. KurtSiefer *et al.* reported a figure of 39 photons per sr in an avalanche with 4×10^8 electrons, resulting in a lower limit of 2.5×10^{-6} photons per electron, where the detector's spectral response has been partly accounted for, and self-absorption was not [26]. A measurement accounting for both the optical system and self-absorption was presented by Lacaita [29], with an emission efficiency of 2.9×10^{-5} photons with energy higher than 1.14 eV per carrier crossing the junction. Electroluminescence yield for InP has not been reported till date. As outlined earlier, it is expected to be significantly higher than that of silicon, and is conservatively estimated to be

Fig. 3. Cross section of the proposed device: an InGaAs SPAD is direct-bonded to a Si SPAD for optical readout. IR photons are incident on the back surface of the InGaAs SPAD (e.g., [9], [11]). As carriers recombine during the avalanche, they release NIR and visible photons, which are detected by the silicon device (e.g. [5]). The devices are fused through their silicon-dioxide passivation layer, eliminating the need for lattice matching between the two semiconducting materials.

2.9×10^{-4} photons per hot-carrier for the purposes of our calculation.

III. MODEL FOR UPCONVERSION EFFICIENCY

A. Upconversion Model

The model proposed in this work is based on the hot-carrier luminescence effect described earlier. Fig. 3 illustrates a device based on this concept, comprised of an InGaAs/InP SPAD fused to a silicon CMOS SPAD. A primary IR photon is absorbed in the narrow-bandgap InGaAs layer, and the photogenerated charges are swept to the high-field multiplication region. During avalanche multiplication, secondary photons are emitted from the multiplication layers and are detected by the silicon SPAD, and processed on the same die. This upconverting hybrid pixel can be scaled to large arrays for parallel operation, for example in single-photon near-infrared (NIR) imaging applications. A metal masking layer is used to minimize interpixel crosstalk.

We wish to investigate whether a sufficient number of secondary photons are emitted per primary avalanche for them to be detected with high probability, how their detection will affect the bandwidth of the hybrid system, and what will be the power consumption of such a scheme.

In order to calculate the overall detection probability of the up-conversion scheme, we need to multiply the primary NIR detection probability in the InGaAs/InP SPAD, by the emission probabilities (as a function of wavelength) of the electroluminescent photons emitted toward the silicon SPAD. We should then account for self-absorption in the InP device. Finally, we need to determine the probability of absorption of these photons in the silicon SPAD's depletion region, and calculate the avalanche initiation probability of the photogenerated charge

carriers. Mathematically, the upconversion probability can be expressed as

$$\eta_{uc} = \int_{E_{gs}}^{E_{max}} \int_{x_{j2}}^{x_{j2}+x_d} \frac{\Omega}{4\pi} N_{sp}(\hbar\omega) [1 - P_{sa}(\hbar\omega, x_{j1})] \times P_{abs}(\hbar\omega, x_{abs}) P_{av}(x_{abs}) d(\hbar\omega) dx_{abs} \quad (2)$$

where Ω is the solid angle subtended by the silicon junction when seen from the InP junction; N_{sp} is the number of electroluminescent photons at energies $\hbar\omega$; emitted in a primary avalanche; $P_{sa}(\hbar\omega, x_{j1})$ is the probability of self-absorption of the secondary photons, which is a function of their energy and generation depth x_{j1} ; P_{abs} is the absorption probability in the silicon SPAD's depletion region, which extends from x_{j2} to $x_{j2} + x_d$; and $P_{av}(x_{abs})$ is the probability for an electron-hole pair photo-generated at x_{abs} to induce a detectable avalanche.

In Section II-B-E, we will develop expressions for these parameters that will allow us to compute the overall up-conversion efficiency of the device.

B. Secondary Photon Emission Toward the Silicon Junction

An avalanche event in a SPAD can be viewed as a discharge of the junction capacitance C_j from an initial voltage, in excess of the diode's breakdown voltage to approximate the breakdown voltage. The total number of electrons flowing during an avalanche is

$$N_e = \frac{1}{q} (C_j + C_p) V_{ob} \quad (3)$$

where q is the electron charge (in Coulomb), C_j is the junction capacitance, C_p is any additional capacitance seen by the junction, including interconnection and sensing capacitances, and V_{ob} is the overbias above breakdown.

The number of secondary photons emitted from the primary junction is

$$N_{sp}(\hbar\omega) = \eta_e s(\hbar\omega) N_e \quad (4)$$

where η_e is the luminescence yield per electron (in relevant energies for Si absorption) and $s(\hbar\omega)$ is the normalized spectral distribution of the secondary photons, shown in Fig. 2. In reality, additional photons are expected to be emitted from the charge region between the absorption and multiplication regions, where the high electric field is lower than the breakdown field, and thus, recombination events are highly likely. In this analysis, we conservatively disregard these photons, and assume all secondary photons are emitted from the maximum field region at the junction plane.

We can assume an isotropic emission from the junction plane. Consequently, only a fraction of the emitted photons $\Omega/4\pi$, is actually transmitted towards the silicon junction. The solid angle Ω for the case of a planar InP junction emitting towards a parallel planar silicon junction can be approximated by assuming all photons are emitted from one of the vertices of the InP rectangular junction (Fig. 4). This will provide a lower bound on the actual flux emitted towards the silicon SPAD. The solid angle subtended by the detector from this vertex is approximated

Fig. 4. Geometrical construction for calculating the percentage of photons emitted from an InP junction plane onto a Si junction plane. A conservative approximation places all avalanching charges at one of the vertices of the emitting plane.

by [30]

$$\Omega = \tan^{-1} \frac{d^2}{S\sqrt{2d^2 + S^2}} \quad (5)$$

where d is the side dimension of the Si junction and S is the vertical distance between the junctions.

On combining (3)–(5), we get

$$\frac{\Omega}{4\pi} N_{sp}(\lambda) = \frac{1}{4\pi q} \tan^{-1} \frac{d^2}{S\sqrt{2d^2 + S^2}} \eta_{es}(\lambda) (C_j + C_p) V_{ob}. \quad (6)$$

C. Secondary Photons Self-Absorption Probability

Self-absorption in InP reduces the number of photons that reach the surface. For simplicity, we assume all luminescence occurs at the junction plane, a distance x_{j1} from the surface. The emitted photon population will be

$$N_{surf}(\hbar\omega) = \frac{\Omega}{4\pi} N_{sp}(\hbar\omega) [1 - P_{sa}(\hbar\omega, x_{j1})] = \frac{[\tan^{-1} \frac{d^2}{S\sqrt{2d^2 + S^2}} \eta_{es}(\hbar\omega) (C_j + C_p) V_{ob}] \exp(-\alpha_{InP}(\hbar\omega) x_{j1})}{4\pi q} \quad (7)$$

where $\alpha_{InP}(\hbar\omega)$ is the absorption coefficient in InP.

D. Secondary Photon Absorption Probability in Silicon

Having calculated the spectral distribution of the emitted photons, we can estimate the probability for these photons to be absorbed by the Si SPAD, as well as their probability of generating an avalanche. Here, we assume that reflections at the interfaces do not substantially affect the number and spectral distribution of secondary photons.

We have shown that in a shallow trench isolation (STI)-bounded shallow junction, the high field region is highly localized in the depletion region of the junction [5], so we can assume all absorption occurs within the depletion region. The probability for N photons of energy $\hbar\omega$ to generate an electron-hole pair within this layer is

$$P_{abs}^N(\hbar\omega) = 1 - \{1 - P_{abs}(\exp[-\alpha_{Si}(\hbar\omega) w_d] - \exp[-\alpha_{Si}(\hbar\omega) (x_{j2} + w_d)])\}^N \quad (8)$$

where α_{Si} is the absorption coefficient in silicon, w_d is the depletion width, and x_{j2} is the junction depth in the silicon device. The depletion width of the junction can be determined from the analytical expression for a one-sided linearly graded junction (e.g., as given by Sze [15])

$$w_d = \left(\frac{3V_B \epsilon_s}{2qa} \right)^{1/3} \quad (9)$$

where V_B is the sum of applied and built-in voltages, ϵ_s is the dielectric constant of silicon, q is the electron charge, and a is the grading coefficient of the linearly graded junction.

The total upconverted photons' absorption probability in silicon can now be calculated using (7)–(9) over all relevant wavelengths.

E. Secondary Avalanche Initiation Probability

Next, we need to calculate the probability that an absorbed photon will induce an avalanche. For a one-sided, linearly graded p–n junction, Poisson's equation translates to a field distribution

$$E(z) = \frac{qa}{2\epsilon_s} (w_d^2 - z^2). \quad (10)$$

We approximate the avalanche probability as a function of the position of generation of the electron–hole pair by solving the coupled differential equations [31]

$$\frac{dP_{be}}{dz} = (1 - P_{be}) \alpha P_{bp} \quad (11a)$$

$$\frac{dP_{bh}}{dz} = (1 - P_{bh}) \beta P_{bp} \quad (11b)$$

where P_{be} and P_{bh} are the avalanche initiation probability by an electron and a hole, respectively, α and β are the ionization rates of electrons and holes, respectively, and P_{bp} is the joint avalanche initiation probability

$$P_{bp} = 1 - (1 - P_{be})(1 - P_{bh}) = P_{be} + P_{bh} - P_{be}P_{bh}. \quad (12)$$

These equations can be solved numerically to provide the avalanching probability (Fig. 5).

IV. NUMERICAL CALCULATIONS AND DESIGN CONSIDERATIONS

In order to test the feasibility of the proposed upconversion scheme, we use the model developed in the previous sections. The self-quenched InGaAs/InP SPAD has an active area of $15 \mu\text{m}$ per side and a junction capacitance of 150 fF, dominated by the capacitance of the depleted region. Due to the optical readout, the off-chip routing and the sensing circuit's capacitance, which can be of the order of a picofarad in SPADs with electrical readout, are eliminated. The passivation thickness of a 6-metal-layer silicon device (as was used in [5]) is of the order of $7 \mu\text{m}$, so InP-SPAD/Si-SPAD capacitance is negligible. The SPAD operates at an overbias of 5 V with a junction located 200-nm below the surface. For the silicon detector, we compare the performance of two commercially available detectors [32], [33].

Fig. 5. Numerical analysis of electron, hole, and total avalanche initiation probabilities (P_e , P_h , and P_p) as a function of photon absorption depth in a Si SPAD, following (11) and (12).

Fig. 6. Junction and surface electroluminescence spectral densities for the 200-nm deep InP junction. The latter accounts for only those photons emitted towards the silicon junction. Absorption coefficients were taken from [34].

From (3), we can estimate that 4.7×10^6 electrons flow during an avalanche, and from (4), we calculate that 131 photons are emitted isotropically in the silicon absorption band from the junction. The spectral density of these photons is shown in Fig. 6, both at the junction and using (7), at the surface of the InGaAs/InP SPAD.

The upconversion efficiency can now be determined using the emitted spectral density and the sensitivity of the silicon detector. Results indicate a 97% detection probability for the Cova device (at 5 V overbias) [33] and 91% for the Rochas SPAD [32]. These numbers can be further raised if the total charge flowing in the InGaAs/InP SPAD is increased (Fig. 7), or by increasing the silicon junction's depletion width, thereby, increasing its detection efficiency for long wavelengths.

Because the silicon SPAD will also generate electroluminescent photons, it is important to prevent a positive feedback loop between the junctions. This can be achieved by controlling the dead time of the IR SPAD, so that it overlaps the avalanche time of the silicon device.

The power dissipated during the upconversion process is the sum of the powers dissipated during the InP and silicon

Fig. 7. Numerical simulation of internal up-conversion efficiency as a function of primary SPAD's junction capacitance.

avalanche. These can be estimated as the product of the junction capacitances by their overbias, resulting in approximately 1 pW per detected photon, significantly lower than reported schemes [35].

V. CONCLUSION

We proposed and analyzed a novel method for single-photon upconversion. The benefits of the proposed scheme are fourfold: it offers wire-free, parasitic-free, and massively parallel interconnection between the IR-SPAD and the CMOS silicon SPAD, enabling large-scale array integration of III-V SPADs; the elimination of bumps allows for high pixel density and high fill factors; the low-temperature glass-to-glass bonding processes replaces large-array flip-chip bonding, which would be otherwise required and greatly simplifies the manufacturing of the hybrid devices; and it reduces avalanche charge, resulting in lower power and reduced afterpulsing.

In order to achieve upconversion, this method utilizes a natural byproduct of the avalanche process, specifically the spectral component of the electroluminescent photons, which is higher than the bandgap of the absorbing material of the detector. We demonstrated analytically that a silicon SPAD with a spectral response similar to commercially available devices, can detect these secondary photons with a 91%–97% detection probability, resulting in a high-efficiency low-power upconversion scheme.

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Hod Finkelstein (S'03) received the B.Sc. degree (with distinction) from Cornell University, Ithaca, NY, and the M.Sc. degree from the Technion-Israel Institute of Technology, Haifa, Israel, both in electrical engineering, in 1994 and 1998, respectively. He is currently working toward the Ph.D. degree in electrical engineering from the University of California-San Diego, San Diego.

His research interests are in modeling, design and application of single photon detectors for biology and communications, and in the design of their support circuitry. He worked as a Mixed-Signal Design Engineer at Intel's Haifa design center. He was later responsible for semiconductor manufacturing and test technologies, and for device reliability, as Vice President of Operations at a number of fabless companies.

Matthias Gross was born in Kamen, Germany, in 1970. He received the diploma in physics from the University of Dortmund, Dortmund, Germany, and the Dr.-Ing. degree in electrical engineering from the University of Duisburg, Duisburg, Germany, in 1995 and 2001, respectively.

He is currently with the optoelectronic computing group at the University of California-San Diego, San Diego. Earlier he was working with the Fraunhofer-Institute for Biomedical Engineering in St. Ingbert, Germany. His research interests include optoelectronics and biophotonics with an emphasis on optical interconnects.

Mr. Gross is a member of the German Physical Society.

Yu-Hwa Lo received the B.S. degree from National Taiwan University, Taipei, Taiwan, and the M.S. and Ph.D. degrees from the University of California-Berkeley, Berkeley, in 1981, 1986, and 1987, respectively, all in electrical engineering.

He worked for Bellcore (now Telcordia) as a Member of Technical Staff from 1988 to 1990. He joined the faculty of School of Electrical Engineering, Cornell University as an Assistant Professor in 1991, and then, became an Associate Professor in 1996. He is currently with the Department of Electrical and Computer Engineering at the University of California-San Diego (UCSD), San Diego, where he became a Professor in 1999. His research interests include biophotonics, fluidic-photonics integrated circuits, and fluidic tunable optics. He was a co-founder of Nova Crystals, an optoelectronic component company for telecommunication, and has served as the CTO and Board Director till March 2004. He also founded Rhevision Technology to commercialize the technology of fluidic tunable optics for miniaturized imaging systems in 2004. He has published more than 300 refereed papers in technical journals and conference proceedings. He holds 18 patents.

Dr. Lo is the Chairman of the Integrated Optics and Optoelectronics Committee for LEOS, Chairman of the 2006 LEOS summer topical meeting on optofluidics, and committee member of several international conference proceedings. He is a Fellow of the Optical Society of America. He is an Associated Editor of the IEEE PHOTONICS TECHNOLOGY LETTERS.

Sadik Esener (S'79–M'81–F'87) received the Ph.D. degree in applied physics and electrical engineering from the University of California-San Diego (UCSD), San Diego, in 1987.

He joined the Department of Electrical and Computer Engineering at UCSD in 1987, where he became an Associate Professor and a Full Professor. He is currently the Director of the Nano Tumor Cancer Nanotechnology Center of Excellence at UCSD, where he earlier directed the DARPA Opto-Center for Heterogeneously Integrated Photonic Systems (CHIPS). He is the author of five book chapters, more than 100 journal papers, and more than 350 conference proceeding papers. He holds 15 patents.

Prof. Esener is a Fellow of the Optical Society of America, and is also the co-founder of five San Diego-based companies.