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Pure Ge and Novel Ge Based Separate Absorption and Multiplication Single Photon Avalanche Diodes for Enhanced Count Rates at 1310 nm

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Malcolm Carroll, Ph.D.
Sandia National Laboratories
P.O. Box 5800
Albuquerque NM, 87185
Ph. (505) 284-3499
Fax (505) 844-8985
mscarro@sandia.gov

Executive Summary

Research Direction

This IC post-doc research effort is pursuing novel single photon detector avalanche photodiodes (SPAD) designed to greatly reduce after-pulsing effects. Reduction of after-pulsing will reduce hold-off times, used to discharge trapped charge, and increase the maximum achievable count rate for Geiger mode (GM) operated avalanche photodiodes (APD). A general principle of this work will be to focus on using low charge-trap containing materials for absorption and multiplication. In particular, examination of commercial pure germanium APDs and novel germanium SPAD based designs (i.e., separate absorption and multiplication (SAM) regions integrated with wider band gap near lattice matched materials like GaAs or SiGe) are being evaluated. The focus on germanium based detectors is motivated by reports that Ge has 10^2-10^3 fewer charge traps densities than InGaAs/InP the leading near infrared (NIR) GM-APD technology. The significant decrease in traps and therefore after-pulsing expected in these novel Ge detector structures represents a possible increase in maximum achievable count rates by over an order of magnitude compared to InGaAs/InP SPADs.

Overview of Accomplishments

The IC Postdoctoral Research Fellow began work on this project in August, 2007. The primary milestones that the post-doc has achieved are: (1) developed the required understanding and skill to do passively gated NIR GM-APD measurements; (2) modified the existing the SNL GM-APD set-up to do measurements up to 100 MHz and significantly improved the data acquisition system to allow significantly more thorough characterization of the APDs; (3) completed initial measurements of commercial Ge APDs which show promising high frequency characteristics; (4) submitted a conference paper on the Ge SPAD characterization (SPIE, Orlando, March, 2008); (5) contributed to a DARPA workshop on SPAD development (Nov., 2007); (6) successfully adapted the single photon detection approach to single ion detection for ultra low straggle single ion implantation, which has demonstrated orders of magnitude increase in sensitivity relative to a control analog gain APD approach and is part of work to be presented in an invited talk at ??? and (7) is beginning to develop numeric TCAD capability to simulate SPADs in collaboration with D. Yoder at Georgia Tech. Single ion implantation capability is a technique being developed both for advanced CMOS and quantum computing fabrication. Furthermore, in collaboration with Dr. J. Cederberg at SNL, development of a GaAs on pure Ge epitaxial capability has been developed. GaAs is nearly perfectly lattice matched with Ge allowing for novel separate absorption and multiplication APD designs to be fabricated that would leverage the advantages for the more mature Ge and GaAs material systems compared to InGaAs/InP (i.e., charge traps).

Plan for future 7 months

The recent promising high frequency results observe in the Ge APDs tested in this first 5 month phase using passively gated Geiger mode (described below) motivate additional characterization of different kinds of commercially available pure Ge APDs and examination of more aggressive novel Ge based SAM-SPAD designs (e.g., GaAs/Ge or SiGe/Ge SAM-SPAD). To pursue novel Ge SAM-SPAD designs both numerical TCAD will be used to better evaluate the theoretical benefits of these structures while parallel fabrication development will be pursued to clarify the feasibility of building novel structures like GaAs/Ge APDs, which is currently not available elsewhere. TCAD development will use a combination of existing device simulation tools and collaborative work with D. Yoder at Georgia Tech. Evaluation of novel fabrication approaches like building Ge SPADs in the SNL 6", 0.35 um CMOS fabrication facility and using GaAs/Ge epitaxy to build SAM-SPAD devices will be characterized to evaluate internal fabrication techniques. The goal for the next 7 months is to measure internally fabricated pure Ge APDs and evaluate the quality of GaAs epitaxy on Ge substrates (i.e., etch pit density and photoluminescence to establish crystal quality).

1. Technical Details & Identification and Significance of the Problem

There is great interest in the area of single photon detectors coming from a wide range of applications including: single molecule fluorescence detection[3], quantum computation with linear optics[4], linear quantum cryptography[5], eye-safe LIDAR (Light Detection and Ranging)[6] and QKD[7]. In the area of single photon detectors there are several methods by which to achieve single photon detection namely the photomultiplier tube (PMT), microchannel plate (MCP), charge coupled device (CCD), superconducting single photon detector (SSPD)[8], and the Geiger-mode avalanche photodiode or *SPAD*[9]. Interest in SPADs is motivated by advantages like easier integration for imaging arrays and practicality for communication networks (e.g., cost and operation temperature). Furthermore, SPAD development can leverage the tremendous amount of previous work that went into detectors for optical networking.

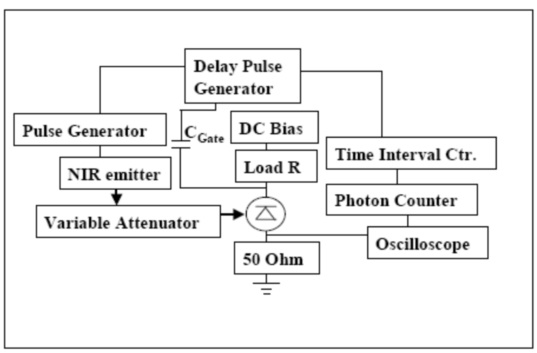
Growing interest in using 1310 nm as well as 1550 nm for applications like QKD suggests that Ge SPADs may still be of interest despite the much weaker 1550 nm absorption length for cooled Ge SPADs. There are several other added benefits that using Ge SPADs affords, by virtue of Ge being a more mature material system than the more recently developed InGaAs/InP system. Germanium has a long development history for which very strict requirements on material quality were required to achieve X-ray detectors with simultaneously extremely large depletion regions and low dark currents. Very high purity low defect crystal manufacturing capabilities have been established for this purpose and Ge can now be fabricated with trap densities that are several orders of magnitude lower than in InGaAs/InP[2]. The growing development of silicon based photonics and integration of Ge based devices on the Si CMOS platform also may offer future opportunities for Ge SPADs, for example, using advanced circuit integration for ultra fast active quenching circuits with Ge SPADs (e.g., low parasitics). Fast active quenching offers the ability to reduce the amount of trap charging during every detection window, which is also known to greatly improve after-pulsing effects.

Methodology

The SPAD tested is from Judson Technologies LLC; it is a J16A-18A-R050U. The J16A designates a series of Ge p+/n diode Avalanche Photodiodes (APD) that are designed for high-speed applications (with bandwidths up to 1.5GHz) from 800 nm to 1310 nm. This detector has a manufacture's specified low dark current on the order of 100 nA at room temperature under reverse biasing. The 18A is packaging designation which was modified to fit into a 14 pin chip carrier used in the laboratory cryostat. The R050U identifies this APD as a 50 µm diameter active region detector.

The APD was characterized in both linear mode and GM. Geiger mode or SPAD operation consists of operating the APD above the breakdown voltage (V_{BD}) of the diode in combination with a quenching mechanism to stop the breakdown and allow the junction to reset. When the junction is initially biased above breakdown there is a period of time that the junction is over-biased but has no current flowing through it. Avalanche breakdown is initiated by either photon absorption or a carrier entering into the high field region from the low field regions of the device (e.g., thermal generation). In this time before a dark count avalanche, if a photon generates an electron or a hole that is subsequently injected into this high field region it will be detected as a large avalanche pulse. The breakdown, in Geiger mode, is subsequently quenched in a number of ways including gating the bias so that it is above breakdown for only short intervals of time, actively sensing the breakdown and dropping the voltage, or passively quenching the breakdown by using a high series resistance. Here the first and/or last methods are used to quench an avalanche in the SPAD.

A schematic of the Geiger mode measurement set-up is shown in Figure 1(a). The measurement set-up includes the capability to gate with detection windows of 4 ns to 10 µs at frequencies between 1 kHz to 100 MHz where the gate pulse length is 20 ns with 5 ns rise and fall times. A well characterized 1310 nm semiconductor laser is used for a low-photon number light source. This laser is triggered with a pulse generator for 2ns FWHM and attenuated down with a 20 dB fixed in-line attenuator in series with a variable attenuator at 46 dB such that there is on average one photon per pulse incident on the SPAD. The pulse generator that drives the laser is triggered by a second pulse generator that gates the SPAD above breakdown. A photon counter and time interval counter are used to measure dark count rates (DCR) and detection efficiency (DE). DE is a product of quantum efficiency and breakdown probability. The quantum efficiency determines how well the detector absorbs light and makes photo-generated carriers. The breakdown probability determines how likely it is for those photo-generated carriers to cause breakdown. The SPAD is mounted within a cryostat shown in Figure 1(b), which enables measurements from 16 K to room temperature.



(a)

(b)

Fig. 1. (a) A schematic diagram of the Geiger mode experimental set-up. (b) A photograph of the laboratory set-up, the cryostat used is on the right with the vacuum can removed.

DATA

The responsivity of the J16A-18A-R050U APD was measured from 1 to 15 V reverse bias at room temperature over 30 dB of 1310 nm light intensity and shown to be with in manufacture's specifications (> 0.60 A/W) at 0.64 A/W. This results in extrinsic quantum efficiency (QE) of

60.5%. The responsivity quickly dropped an additional 0.1 A/W by 250 K, after which time it was independent of temperature to within the error of the measurement. The reduced temperature QE is therefore 51%; this thereby limits the upper DE to 51% for reduced temperature SPAD measurements for this particular Ge APD, if the breakdown probability (BP) were 100%, since $DE = QE \times BP$.

Linear mode operation

Room temperature and reduced temperature current-voltage (I-V) measurements were made to characterize the dark current performance and optical response, Figure 2(a). The current response of the Ge device shows good rectification and a flat leakage current dependence at reverse biases, between 1 V and 20 V, up to the commencement of multiplication gain in the junction at 22 V, 26 V, and 29 V at 77 K, 150 K and 300 K, respectively. The measured room temperature dark currents are at manufacture's specifications by being ~30 nA in the flat region. A relatively flat photoresponse is observed at all temperatures up to the commencement of multiplication gain over 20 V. The multiplication gain is calculated as:

$$Multiplication = \frac{I_{photo} - I_{dark}}{I_{photo}(1V) - I_{dark}(1V)}.$$

Gain is approximately 10 – 20 before the current rises rapidly above compliance. The reduction in the dark current between 150 K and 77 K is small compared to the large dark current reduction from 300 K to 150 K. Weak temperature dependence of dark current is often ascribed to tunneling contributions to the dark current. It is unclear whether this component is from a shunt leakage path or in the junction itself. Perimeter leakage paths do not contribute to dark counts in GM. In Figure 2(b) the dark current of the device is displayed in an Arrhenius plot as a function of the inverse of temperature showing the initial steep fall off of thermally generated dark current, which by T ~ 200 K is subsequently dominated by a weakly temperature dependent term.

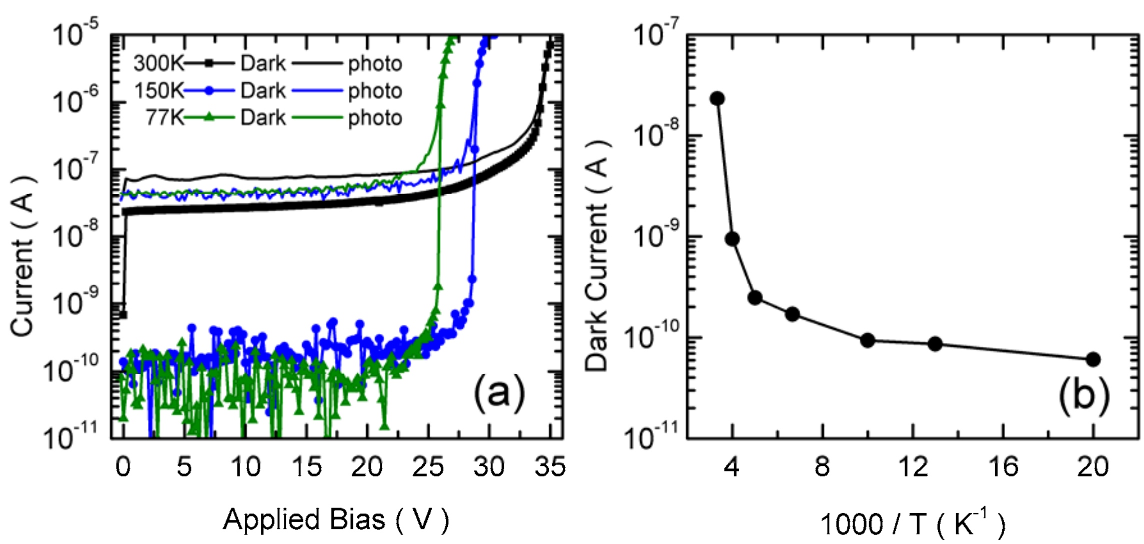


Fig. 2. (a) Dark current and photocurrent I-V measurements of the Judson Technologies GE APD at 300 K, 150 K, and 77 K. (b) Arrhenius plot of the dark current as a function of 1000/T at an integrated average from 1 to 10 V applied bias.

Geiger mode operation

In order to reduce dark counts, SPADs are generally operated below room temperature. When the operating temperature of the Ge APD was decreased, the dark current decreased and the breakdown voltage is reduced; as is apparent in the I-V curves in Figure 2(a). V_{BD}, measured at a dark current of 300 nA, was 33.84 V, 28.87 V, and 25.87 V at 300 K, 150 K, and 77 K, respectively. The Ge APD was run in Geiger mode by bringing the reverse bias (V_{BIAS}) near the V_{BD} and then pulsed excess voltage by an additional 5 V (V_{GATE}) during a short (20 ns) gate pulse. The excess voltage (V_{EV}) is thus equal to $V_{BIAS} + V_{GATE} – V_{BD}$. The gate pulses were delivered at a series of rates: 1 kHz, 5 kHz, 10 kHz, 50 kHz, 100 kHz, and 500 kHz, with a rise and fall time of 5 ns. A consequence of the APD being biased above V_{BD}, as previously discussed, is that during the gate pulse a single optically or thermally generated carrier could initiate avalanche breakdown and thereby create a significant current (typically about 0.2 mA). This avalanche process enables the sensitivity to single photons. Once current begins to flow, then some of the applied voltage drops over the 50 ohm sense resistor and thereby, generates a measureable signal to be sent to the discriminator on a photon counter. The SPAD is subsequently quenched by the reduction of V_{GATE}. In order to demonstrate single-photon sensitivity, the 1310 nm laser was pulsed for a short time (2 ns) during the SPAD gate pulse, while looking for a Geiger pulse that coincided with the photon arrival time at the APD. The optical pulse amplitude was attenuated such that an average of 1 photon arrives at the APD per pulse. For the pulsed laser measurements, the 1310 nm laser was biased to 6.3 mA (near threshold). The electrical pulse went through a 6 dB 50 ohm attenuator, which reduced the pulse voltage amplitude from 800 to 400mV, and then the pulse was applied to the laser diode cathode through a series connected 50 ohm resistor and 1000 pF capacitor. Thus, the 400 mV voltage pulse was converted to an 8 mA current pulse, 2 ns in duration (FWHM). This gives a predicted optical power of 1 mW at the peak of the pulse. Multiplying this by the transmission of the cryostat window (0.90), by the transmission of the window on the 18A packaging (0.91), and by a reduced area factor of 0.38 (coming from the 81 µm laser diameter and the 50 µm diameter detector), yields an photon flux of 2.06×10^6 photons per nanosecond. Multiplying this flux by the pulse width (2 ns), and an attenuation of 66 dB yields an average of 1 photon per pulse. The incoming photons are of Poisson distribution thereby resulting in a 36.8% chance of 0 photons in any given pulse; this has been taken into account when calculating the DE.

RESULTS

The DCR dependence on overbias and temperature is shown in Figure 3(a). A low gate pulse frequency (f_{gate}) of 1 kHz with a corresponding gate pulse length (T_{on}) of 20 ns is used for the baseline DCR as a function of the temperature in the SPAD. The DCR is approximated using $DCR = \frac{N_{counter}}{T_{on} f_{gate}}$, with $N_{counter}$ being the number of counts measured by the photon counter in one second. This expression correctly accounts for the dead time when the detector is held-off. Starting at this low frequency ensures that the baseline DCR is minimally impacted by after-pulsing through use of a long hold-off time (T_{off}), where $T_{off} + T_{on} = 1/f_{gate}$.

The DCR in Figure 3(a) is over five times larger at 150 K than 77 K at V_{EV} = 3 V, which clearly shows a much weaker temperature dependence than from what might be expected from thermally generated carriers migrating into the high field region. This suggests that a tunneling mechanism is also dominating the dark count rate at low frequencies below 150 K, as is seen in Figure 2(b) for the DC case. In Figure 3(b) the DCR is plotted as a function of the applied reverse bias on the SPAD at 77 K. V_{BD} is constant for all of the traces in Figure 3(b) as is the temperature. When T_{on} = 20 ns the DCR are nearly independent from the f_{gate} from 1 kHz up to 100 kHz, and even at 500 kHz DCR is independent of f_{gate} up to an applied bias of 24.5 V. (The source of the jump in DCR in Figure 3 is under further investigation.) A rapid increase in after-pulsing is typically reported to occur above ~ 100 kHz for InGaAs/InP[10], which is not observed in this Ge SPAD. This observation is one of the critical points of this study, that higher frequency operation of Ge SPADs does not appear detrimentally to affect the performance as much as is reported in InGaAs/InP.

We note that the DCR appears to decrease at high applied bias for 500 kHz compared to the 1 kHz – 100 kHz case. This reduction in DCR at high f_{gate} could be due to increased charging of majority carrier traps in the junction that shift the breakdown voltage[10] or that the DCR curves are the same and the jump in DCR at 500 kHz has been pushed out farther. At the higher frequency these traps may be less able to charge and discharge rapidly enough to recover the low frequency breakdown voltage. A higher breakdown voltage would effectively produce a smaller overbias which

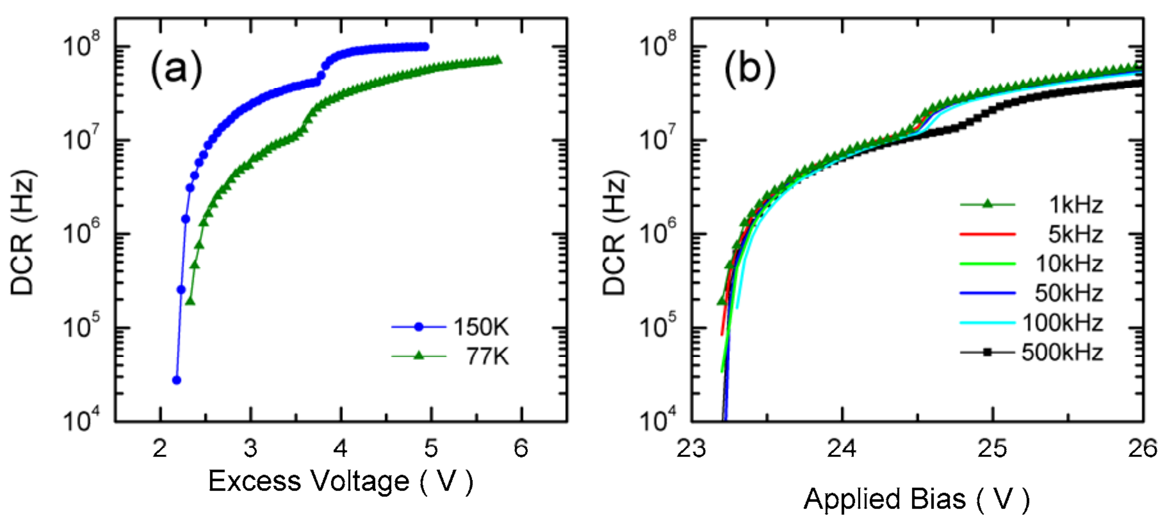


Fig. 3. (a) DCR as a function of V_{EV} for 150 K and 77 K with a 20 ns wide gate pulse length at 1 kHz. (b) DCR as a function of the applied reverse bias on the SPAD at 77 K. The frequency is increased by half decades from 1 kHz to 500 kHz, while T_{ON} is 20 ns.

would reduce the DCR as illustrated in Figure 3 (a). This effect appears to increase in magnitude with higher frequency operation. To better characterize the high frequency DCR performance penalty, bias points were established for a fixed DE at every frequency.

In Figure 4 the DCR is plotted as a function of the DE for ranging from 1 kHz to 500 kHz at 150 K and 77 K up to the maximum measured DE for each frequency. The DE is the combined probability of two events happening consecutively, generation of a carrier from the absorption of a photon, and the triggering of the avalanche process to yield a detectable signal. Detection efficiencies in InGaAs/InP SPADs are usually in the range of 10% - 30% while still maintaining sufficiently low DCRs to achieve useful operation. This Judson Ge APD was not designed for GM operation and one manifestation of this is a relatively low QE (51%) at the low temperatures as well as a junction that was not designed to maximize the probability of producing an avalanche once the photon is absorbed. In other words,

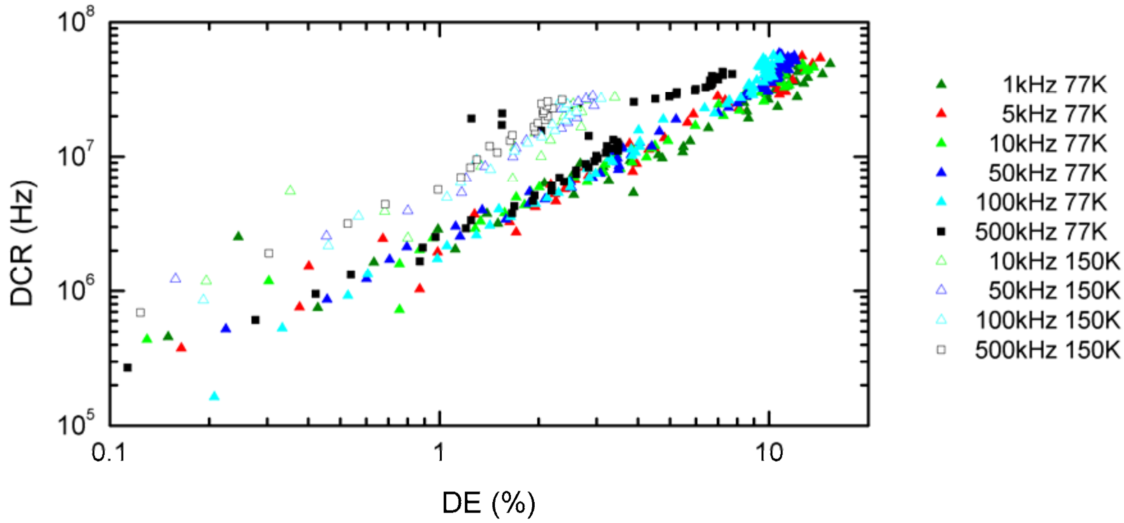


Fig. 4. The DCR is plotted as a function of the DE for two temperature sets (150 K and 77 K).

this device was designed for high gain, typical of APD operation, and not breakdown probability. This leads to higher DCRs at modestly high DE, Figure 4. Even in this non-ideal case we note that at the higher frequency operation range a DE of ~ 15% was achieved with a DCR comparable to commercial InGaAs/InP SPADs specifically designed for GM operation[10]. Much higher frequency operation of this Ge SPAD was furthermore achievable without the rapid rise in DCR that is observed in the InGaAs/InP SPADs, although some performance penalty is still observed in the Ge SPAD like reduced maximum DE.

In Figure 5 the DCR is shown for a DE of 1.6% in (a) at 150 K and 77 K, and for a DE of 1.6% and 8% at 77 K in (b). Since f_{gate} is approximately equal to the inverse of T_{off}, (for T_{off} >> T_{on}), the x axis in Figure 5(a) and (b) could be T_{off}^{-1}, as the frequency increases there is a slight increase in the DCR when the SPAD is being pushed well beyond 100 kHz. The rise in DCR for a constant DE is shown by the 150 K data in Figure 5 (a) presumably from after-pulsing that is not seen at 77 K due to permanently trapped carriers. The rise in DCR in the 8% DE data in Figure (b) also could be from after-pulsing. It is apparent that the Ge-SPAD performance is beginning to degrade as the gate frequency is increased above 100 kHz, direct comparison of the rate of degradation in DCR in InGaAs/InP above 10 kHz is much more rapid as is illustrated by the points from A. Tosi et al.[10] also taken with 20 ns gate pulses.

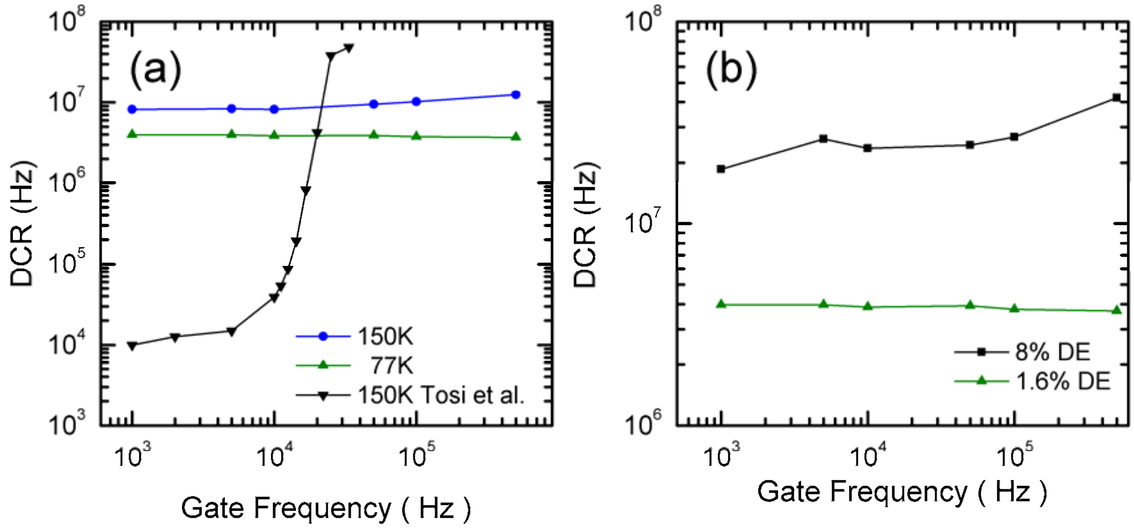


Fig. 5. (a) The DCR is plotted as a function of f_{gate} at a DE of 1.6% for 150 K and 77 K and is compared to the DCR of an InGaAs/InP SPAD at 150 K in Figure 4 of A. Tosi et al.[10]. (b) The DCR is plotted as a function of f_{gate} at 77 K for a DE of 1.6% and 8%.

Summary

Interest in 1310 nm as well as 1550 nm for QKD combined with the desire for increased operation frequency of GM APDs motivates investigation of ways to reduce after-pulsing in SPADs. Previous reports have suggested that Ge APDs have lower trap densities than InGaAs/InP, which are responsible for producing after-pulsing. This paper describes the characterization of a commercially available Ge APD operated in GM at high frequencies. The APD performance in GM (i.e., DE as a function of DCR) is found to be worse than other commercial detectors reported in the literature. A much weaker dependence of DCR on frequency than reported for InGaAs/InP is observed in the Ge APD operated in GM, which is the key observation of this study. Despite the poorer performance of this Ge SPAD at low frequency, the much weaker DCR dependence on frequency leads to better performance at 150 K and at frequencies greater than 25 kHz than reported for commercial InGaAs/InP APDs designed for GM[10]. These initial results are promising that Ge SPADs might provide an opportunity to achieve higher frequency single photon detection rates for 1310 nm QKD.

Note: research results on single ion detection for ultra low straggle implantation can be provided if desired.

2. Technical Objectives

With the available 7 months of funding commercial Ge APDs will be tested to better understand the high frequency performance, TCAD designs of novel Ge and Ge/GaAs SPADs will be evaluated, and initial materials/device characterization will be done to evaluate the possibility of realizing these novel devices:

1. further characterization of higher performance commercial Ge APDs (i.e., characterize after pulsing behavior in commercially available Ge APD with ~ 100 kHz low frequency DCR)
    a. initial cross-over frequency at which Ge has fewer DCR than reported InGaAs/InP is ~200 kHz at ~ 1e7 DCR. Better commercial Ge APDs have been reported and will be obtained. Target cross-over would be 100kHz at ~ 1e5 DCR for passively gated quenching.
2. evaluate different device structures with TCAD
    a. estimate theoretical trade-off of high field regions designed for GM rather than analog gain in pure Ge and GaAs/Ge SAM-SPAD. This should translate into an increase in either operating temperature or detection efficiency for a fixed DCR. Target DE would be ~20-30% at T~200K and DCR ~ 1e5 for passively gated quenching.
3. evaluate internally fabricated Ge APDs
    a. target would be to establish similar DCR and DE as commercially available devices (e.g., Judson Ge APD performance described earlier in this report)
4. evaluate GaAs on Ge epitaxy suitability for Ge/GaAs SAM-SPADs
    a. evaluate defect density of GaAs on Ge (EPD < 1e5/cm^2)
    b. evaluate PL of GaAs on Ge (intensity within factor of 2-3 of GaAs on GaAs epitaxy)

Table 1. Technical Objectives.

Objective	Figure of Merit	State-of-the-art	Achieved	2008
1 commercial Ge SPAD high frequency DCR dependence	After-pulsing on-set frequency	100 kHz	Better DCR @ > 200 kHz observed in initial Ge device tested	Initial device indicates > 500 kHz
2 TCAD design for novel Ge & Ge/GaAs SPAD	DCR @ set DE, Temp & freq.	~ 10 MHz @ 20% & 200 kHz		Target is to reduce DCR < MHz
3 evaluate SNL Ge APD performance	$QE_{internal}$, dark current	Comparable to commercial: $QE_{internal}$ ~ 80-90% and J_{dark} ~ 1 mA/cm^2		
4 evaluate GaAs on Ge epitaxy	Etch pit density (EPD)& photoluminescence (PL) intensity	PL & EPD: calibration comparison to GaAs epi on GaAs		Target – similar GaAs epi on Ge as on GaAs substrates

3. Statement of Work

High frequency passive gated characterization of Ge SPAD (~ 3 months)
Description: the goal of this task is to characterize Ge APDs at high gate frequencies to confirm the hypothesis that the reported order of magnitude fewer traps leads to better after-pulsing behavior. Characterization will be used to (a) establish the limits of the Ge Geiger Mode performance at high frequencies compared to InGaAs-InP; (b) use the device characteristics to establish design choices for better Ge SPAD performance.

Primary metric: establish $f_{after\text{-}pulse\text{-}onset}$ for Ge, where dark counts increase rapidly when $f_{passive\text{-}gating} > f_{after\text{-}pulse\text{-}onset}$. $f_{after\text{-}pulse\text{-}onset}$ ~ 100 kHz for InGaAs-InP when passively gated. This frequency represents the frequency above which improvement is desired.

Note: 1 – 5 MHz has been cited in previous discussion. This number is for active quenching circuitry, which quenches the Geiger pulse more rapidly and leads to an extension of the passively gated frequency. Either number can be used to compare the after-pulsing effect. Since are using passively gated approaches, which has some advantages for characterization, we are now quoting the same value for InGaAs/InP devices.

Model novel SPAD designs (~ 7 months)
Description: the goal of this task is to theoretically estimate trade-offs between 3 different designs compared to standard Ge and InGaAs-InP. The 2 designs proposed are modifications of pure Ge structures optimized for GM instead of analog gain and novel Ge based SAM-SPAD structures like GaAs/Ge, Ge/Si. To make estimates related to after-pulsing and dark count rates we anticipate extrapolating from literature results of measured devices (e.g., measured densities of traps in Ge, GaAs, and InP). This effort will include collaborative work with Prof. D. Yoder of Georgia Tech. who is an expert in modeling avalanche processes.

Primary metric: novel design should predict improvements over standard design particularly for $T_{operation}$, speed, detection efficiency, dark count rates OR lead to persuasive simulation results to down select the approach.

Characterize GaAs on Ge growth for APD structure (~ 7 months in parallel)
Description: GaAs SPADs have shown good Geiger mode performance. GaAs/Ge junctions are lattice matched and can be made very high quality as demonstrated by their insertion into high performance multi-junction solar cells for satellite applications. Details of the junction for an APD is however not well established in the literature (e.g., extent of As in-diffusion into Ge producing diffused n+ doped Ge layer). SNL will grow junctions and characterize them to provide information for device modeling.

4. Relationship with Future Research and Development

Full success for this project would be to demonstrate improved 1310 nm SPAD performance at high frequency. For passively gated InGaAs/InP, typical performance is degraded by rapid increase in dark counts when the detection frequency is increased above 100 kHz. A second success is to highlight a path to improve upon existing commercially available SPAD technology.

The primary supposition of the research proposal was to test whether Ge SPADs would have a smaller performance penalty than InGaAs/InP SPADs at high frequency. If this supposition is shown to be true then pure Ge APDs that are commercially available might be dropped in as replacements for InGaAs/InP SPADs for an immediate performance gain at high frequencies using 1310 nm. Initial results described earlier in this report offer some evidence that there are benefits to using Ge SPADs at high frequencies (i.e., short hold off times).

Furthermore, if this research is fully successful, designs and initial material/device tests would highlight a path to improving the current commercially available standard Ge APD. Advanced Ge and separate absorption multiplication Ge/GaAs SPAD structures would extend the 1310 nm high speed performance benefits and SNL would provide either a source of these future devices or a technology transfer path to a commercial entity if the demand warrants it.

5. Additional potential benefits from this project

Single photon detection is used for a number of different applications and improvements in NIR detection are still desired for many of these applications (e.g., LIDAR). We note that one manufacturing challenge that has been cited for APD arrays for LIDAR is non-uniformity of the breakdown voltage across the wafer (pixel array) producing additional complexity for the control/read-out circuit. A Ge based APD array would benefit from the standard implant based, large area and high uniformity processing capabilities available to standard CMOS fabrication.

A second area that has been directly impacted by the work on SPADs at Sandia National Laboratories is state-of-the-art single ion implantation for advanced CMOS and solid-state quantum computing. Single photon detector technology has been applied to single ion detection to extend the limits of the detection ability, which translates to higher precision placement of the donor. Sensitivity to single electron-hole (e-h) pairs generated by the ion stopping in the semiconductor represents a potentially dramatic increase in sensitivity relative to current state-of-the-art which is limited to sensitivities of the order of 1000's of e-h pairs. Initial proof of principle experiments have been carried out and presented. This work has also, in part, resulted in an invited talk (see table). Furthermore we note that the GaAs/Ge epitaxy system is of interest to the solar cell community for which shared learning and costs is likely beneficial to some degree.

6. Coordination with other project teams

This work is not directly coordinated with any other research efforts. Discussions with Dana Rosenberg (LANL) suggest some interest in testing novel SPDs for 1310 nm at LANL.

7. Deliverables

Deliverable	Year	Recipient
Documentation (research report)	2008	Government
SPIE Quantum Information and Computation IV Conference, Orlando, FL (2008)	2008	QKD Community
Optics Letters publication (intended venue for recent results)	2008	QKD Community
Focused Ion Beams for the 20th International Conference (invited talk)	2008	Ion Beam & Single Donor based Quantum Computing Community

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