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Design and Analysis of Single Photonic Devices For An Inverter Application Using Silvaco Tcad

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Abstract

Single photon avalanche diode (SPAD) and single photon transistor (SPT) has been designed using IV-V compound in cadence virtuoso for an emerging application in the modern quantum cryptography. Previously, they had demonstrated photon detector using single photon avalanche diode with counter for the detection of photons from light energy with low efficiency. For data transmission rate of 20 MHz, photon detection efficiency (PDE) was 13% with after pulsing at 247k and dark count rate (DCR) was high. Further, I have merged the SPAD with SPT to improve the efficiency as 98% at room temperature with reduced dark count probability (DCP). The comparison of single photonic devices with single photon avalanche diode efficiency has been analyzed and delay got reduced with less power.

Keywords: Single Photon Avalanche Diode, Single Photon Transistor, single photon detector, high efficiency, low Dark Count Probability, photon counter, single photon inverter.

Introduction

Very-Large-Scale Integration (VLSI) technology is preferred by most number of emerging industries and is the process of combining thousands of transistors in a device like Integrated Circuits (ICs) chip. VLSI technologies have been developed when the requirement of complex semiconductor and communication purpose, and microprocessor is also a VLSI device. It is mainly developed for reducing area by merging billions of transistors in a single chip or device.

Initially, SSI (Small Scale Integration) emerged for implementing one or more logic gates in a single device. MSI (Medium Scale Integration) emerged for implementing hundred logic gates in a device. LSI (Large Scale Integration) emerged for implementing at least a thousand transistors in a device. VLSI is an emerging technology with millions of gates and billions of individual transistors in a device. Then ULSI (Ultra Large Scale Integration) is nowadays an improving technology preferred by most of the industries for ultra-high speed devices with huge number of gates available in a device. This paper is mainly preferred for ultra-high speed applications.

From previous days, silicon material is used by industrial, market and research people for device implementation. According to Moore's law [1]-[2], for every two years number of transistors implement in a single device gets double. Due to band gap thickness of silicon (i.e. Band gap thickness range is 0.7 for Si), devices gets heated quickly is one of the drawbacks in silicon material. In 2018, the gate transistor will short each other when size gets reduced. One more drawback is that the current is applied for silicon but light energy is applied for InGaAs/InP semiconductor material. There may be a chance for a failure of silicon devices due to transistor shortage. While comparing the wastage of light energy we are using for devices is better, InGaAs/InP [1]-[4] band gap thickness is lower than silicon. InGaAs/InP is better semiconductor material to convert single particle into single photonic energy.

Therefore, nowadays industries are mostly preferred Indium Gallium Arsenic/Indium Phosphate (InGaAs/InP) material instead of silicon material for making device to avoid quickly heat exposure, device bursting, and short circuit between transistors. They made a single photon avalanche diode for photon detector application [5]. Instead of combining all photons, single photon efficiency combination will give better results due to high sensitivity. Nowadays research is going on about single photonic devices using different types of semiconductor material. After that, they had implemented single photon avalanche diode in photon counter with photon detection efficiency for data repletion rate of 20MHz. It increases efficiency with lower intensity of material.

Literature Survey

Single Photon Avalanche Diode (SPAD) [6] designed using InGaAs/InP for counter applications with the mixture of III-V compound semiconductor material. For laser repletion rate of 20MHz at 240k, the dark count probability with Photon Detection Efficiency (PDE) [7]-[11] of 13% is $1.9e^{-5}$. The improved quenching techniques such as self-differencing, sinusoidal gating, and fast gating with matched delay lines or dummy path. The balanced detection has been developed to avoid common mode signal cancellation realized with small avalanche pulses.

For a high-performance InGaAs/InP SPAD using a gated-mode Passive Quenching with Active Reset (gated-PQAR) circuit has been designed with reduced after pulse. They had demonstrated a Quantum Key Distribution (QKD) [12] with a secure bit rate exceeding 1 Mbit/s over 50 km fiber averaged over a continuous 36 hr. period.

Single Photon Detector

Photon sensors (or) photon detectors are sensors of light/other electromagnetic energy. Active-Pixel Sensor (APS) [13]-[14] are image sensors and these sensors are commonly used in cell phone cameras, web cameras, and some DSLR.

A photodiode can be used to generate a continuous signal proportional to the intensity of the field. Similarly for a quantum field, the intensity of a detector is related to the expectation value for the photon intensity. The photon statistics can be quantified using the second order correlation function, also known as the intensity correlation function. For a classical field, the correlation function is bounded by the Cauchy-Schwarz inequality is given by,

$$g^{(2)}\ 0\ \geq 1$$

SPAD has been optimized for Geiger mode counter operation which provides a macroscopic avalanche current pulse. When combined SPAD with appropriate bias and pulse discrimination circuitry, it provides high photon detection efficiency with very low dark count rates for data repletion rates. SPAD photon detectors are available with variety of products includes free-space coupling fiber and then Thermoelectric Cooling (TEC), and turnkey receiver instruments.

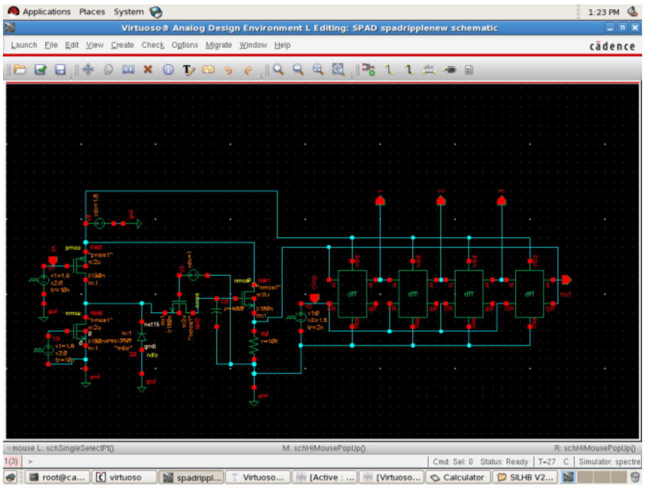

Figure 1: SPAD Photon Detector

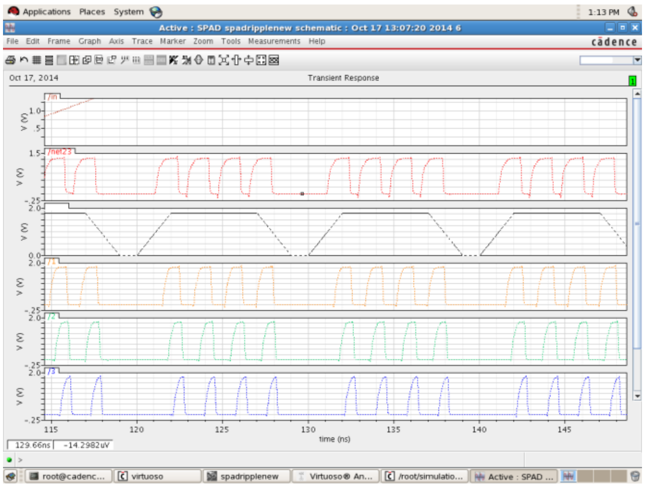

Figure 2: Efficiency of single photon avalanche diode detector

The above schematic diagram in figure 1 shows how single photon avalanche diode work with counter and the simulation result in figure 2 shows the efficiency of existed single photon detector result for numerous counter applications. It shows that for 5MHz input frequency gives approximately 48% PDE at room temperature with low dark count.

Single Photon Transistor

Photon Blockade [6] is the principle of single photon transistor and is based on interaction between a single atom and the mode inside an optical cavity. The interaction causes the cavity to be shifted off resonance with probe laser after the first photon is absorbed. Preventing another photon from entering the cavity until the first photon leaves, this system allows a coherent state to be filtered into a train of single photons; an effect is known as photon blockade or photon turnstile. The resulting output has been observed experimentally for optical cavities and more recently in superconducting microwave cavity where an artificial atom is used to overcome the limited fidelity in optical cavities due to residual motion of the atom.

In empty space, the photon moves at c the speed of light and its energy and momentum are related by E = pc, where p is the magnitude of the momentum vector and derives from the following relation with m = 0 is given by

$$E^2 = p^2c^2 + m^2c^2 --------(1)$$

The energy and momentum of a photon depend only on its frequency (ν) or inversely, its wavelength (λ) is given by

$$E = \hbar\nu = \frac{\hbar c}{\lambda}$$

$$P = \hbar\kappa$$

Where, k is the wave vector and ω = 2πν is the angular frequency is given by

$$k = 2\pi/\lambda$$

$$\hbar = h/2\pi$$

The above equations described for the reduced Planck constant. The magnitude of momentum is

$$P = \hbar\kappa = \frac{h\nu}{c} = \frac{h}{\lambda}$$

The below schematic diagram in figure 3 shows the single photon inverter which is designed using SPAD acts as detector; SPT acts as converter, and is used for counter application. It has been designed in cadence virtuoso using the 180nm technology improves performance prediction than previous single photon detector.

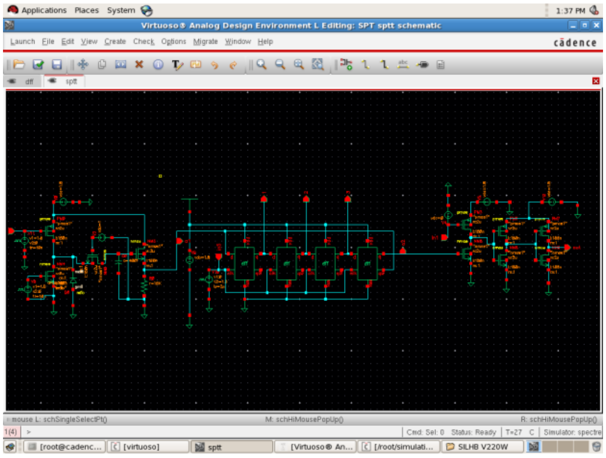

Figure 3: Single Photon Inverter

Experimental Results

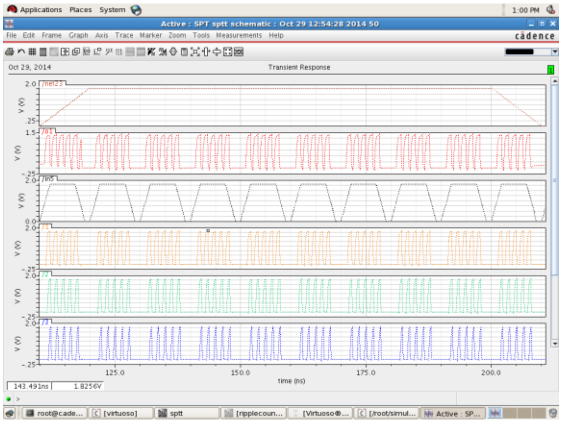

Figure 4: Efficiency of single photon Inverter

The experimental result in figure 4 shows the efficiency of single photon inverter. For the input frequency of 5MHz, PDE is approximately 98% at room temperature with low dark count probability than existing results. The common mode signal cancellation is fully avoided by this method with less delay. In this schematic figure 3, counter is followed by single photon avalanche diode and single photon transistor is followed by counter output.

The single photon inverter is designed using mixture compound semiconductor material with high efficiency as shown in above figure 4 and the comparison table shows the comparison of proposed output with an existing output as follows:

Table 1: Comparison of SPAD with SPD

SL.NO	**PARAMETER**	**EXISTING (SPD)**	**PROPOSED (SPI)**
1	DELAY(s)	112.5 ns	3.012 ns
2	POWER (w)	0.876 mw	1.282 mw
3	INPUT FREQUENCY (Hz)	5 MHz	5 MHz
4	OUTPUT FREQUENCY (Hz)	240.1 MHz	490.8 MHz
5	EFFICIENCY (%)	48.02 %	98.16 %

The table 1. Results show the comparison of proposed Single Photon Inverter (SPI) with existing Single Photon Detector (SPD). The parameters that for comparison are delay, power, input frequency, output frequency, and the efficiency of existing and proposed. In this paper, photon detection efficiency is superiorly increased as 98% from 48% with single photon transistor.

In existing circuit, single photon detector gives 48% efficiency withthe circuit using single photon avalanche diode while in proposed, single photon inverter gives 98% efficiency with the circuit using single photon avalanche diode, photon counter, and single photon transistor.

Conclusion

Single photonic devices have been designed for emerging quantum cryptography using mixture compound semiconductor material with small avalanche pulses to prevent the electronic devices from damage.Power consumption is reduced as 1.282mw for data transmission rate of 5 MHz and delay also got reduced as 3.012ns from existing output 112.5ns; photon detection efficiency (PDE) is 98% with low dark count at room temperature. The comparison table shows the analysis of improvement of photon detection efficiency of proposed and existing system.

Future Enhancement

Furthermore design a single photon avalanche diode and a single photon transistor in Silvaco TCad by giving Atlas Deck input using III-V compound semiconductor material for increasing photon detection efficiency. Photon Detection efficiency gets increases more approximately 35% than existing system. Further, I'll extend my project to an inverter application by giving obtained output from single photon transistor to any load like solar system, motor and so on.

Finally, invoke single photon avalanche diode and single photon transistor which are already designed in Silvaco TCad to cadence virtuoso. From this obtained output, I'll compare my proposed output with existing one.

Reference

[1]. Z.Lu, W.Sun, J.C.Campbell, X.Jiang, M.A.Itzler "Pulsed gating with balanced InGaAs/InP single photon Avalanche diodes", *IEEE J. Quantum Electron.*, VOL.49, NO.5, MAY 2013.

[2]. J.Millaman, C.Halkias, C.D.Parikh, "Millman's integrated electronics", 2010.

[3]. D.Tiarks, S.Baur, K.Schneider, S.Durr, and G.Rempe, "single photon transistor using a fluorescent resonance", *published in quantum physics*, 11 Apr 2014.

[4]. J. Zhang, R. Thew, J. D. Gautier, N. Gisin, and H. Zbinden, "Comprehensivecharacterization of InGaAs/InP avalanche photodiodes at 1550 nm with an active quenching ASIC," *IEEE J. Quantum Electron.*, vol. 45, no. 7, pp. 792–799, Jul.2009.

[5]. L. Xu, E. Wu, X. Gu, Y. Jian, G. Wu, and H. Zeng, "High-speed InGaAs/InP-basedsingle-photon detector with high efficiency," *Appl. Phys. Lett.*, vol. 94, no. 16, pp.161106-1–161106-3, Apr. 2009.

[6]. A.Gallivanoni, I.Rech, and M.Ghioni, ''progress in quenching circuits forsingle photon avalanche diodes'', *IEEE Transactions on Nuclear Science*,Vol. 57, No. 6, Dec 2010.

[7]. M. Liu, C. Hu, X. Bai, X. Guo, J. C. Campbell, Z. Pan, and M. M.Tashima, "High-performance InGaAs/InP single-photon avalanche photodiode," *IEEE J. Sel.Topics Quantum Electron.*, vol. 13, no. 4, pp. 887–894, Jul.–Aug. 2007.

[8]. A. R. Dixon, Z. L. Yuan, J. F. Dynes, A. W. Sharpe, and A. J. Shields, "Continuousoperation of high bit rate quantum key distribution," *Appl. Phys. Lett.*, vol. 96, no.16, pp. 161102-1–161102-3, Apr. 2010.

[9]. Z.Lu, W.Sun, Q.Zhou, J.C.Campbell, X.Jiang, M.A.Itzler, "Improved sinusoidalgating with balanced InGaAs/InP Single Photon Avalanche Diodes", *Optics Express*, Vol. 21, No. 14, pp.: 16716-16721, 15 July 2013.

[10]. Joe C. Campbell, W.Sun, Z.Lu, Mark A. Itzler, and X.Jiang, "Common-ModeCancellation in Sinusoidal Gating with Balanced InGaAs/InP Single

Photon Avalanche Diodes” *IEEE Journal Of Quantum Electronics*, Vol. 48, No.12, pp.: 1505-1511, Dec 2012.

[11]. Xuedong Jiang, Mark A. Itzler, *Senior Member, IEEE*, Rafael Ben-Michael, and Krystyna Slomkowski “InGaAsP-InP Avalanche photodiodes for Single Photon Detection” *IEEEJournal Of Selected Topics In Quantum Electronics*, Vol. 13, No. 4, July/August 2007.

[12]. Mark A. Itzler, Mark Entwistle, and Xudong Jiang “High-rate Photon Counting with Geiger-mode APDs”2011 *IEEE*978-1-4244-8939-8.

[13]. Ryan E. Warburton, Sara Pellegrini, Lionel Tan, Jo Shien Ng, Andrey Krysa, Kris Groom, John P.R.David, Sergio Cova, and Gerald S. Buller “Design, fabrication and characterization of InGaAs/InP single-photon avalanche diode detectors” *OCIS Code*: 040.5570, 040.5160.

[14]. Zhiwen Lu, Wenlu Sun and Joe Campbell, Xudong Jiang and Mark A. Itzler “Balanced Detection in Single Photon Counting” *Advanced Photon Counting Techniques VII, Proc. of SPIE* Vol. 8727, 87270H-1.

[15]. Xudong Jiang, Mark A. Itzler, Kevin O’Donnell, Mark Entwistle, Krystyna Slomkowski “InGaAs/InP Negative Feedback Avalanche Diodes (NFADs) and Solid State Photomultipliers (SSPMs)” *Princeton Lightwave Inc.*, Vol. 8375, 83750U.

[16]. Byoung-Gue Min, Jong-Min Lee, Seong-Il Kim, Chul-Won Ju and Kyung-Ho Lee “Fabrication of Reliable Self-Aligned InP/InGaAs/InP Double Heterojunction Bipolar Transistor with Hexagonal Emitter Mesa Structure” *Journal of the Korean Physical Society*, Vol. 49, December 2006, pp.

[17]. Xudong Jiang, Mark A. Itzler, Kevin O’Donnell, Mark Entwistle, Krystyna Slomkowski “InGaAs/InP Single Photon Avalanche Diodes with Negative Feedback” *Princeton Lightwave, Inc. 2012 IEEE.*

[18]. Zhiwen Lu, Wenlu Sun and Joe Campbell, Xudong Jiang and Mark A. Itzler “Single Photon Detection with Sine Gated Dual InGaAs/InP Avalanche Diodes” *Princeton Lightwave Inc. 2012 IEEE.*

[19]. David A. Ramirez,Majeed M. Hayat, Graham J. Rees, Xudong Jiang, and Mark A. Itzler “New perspective on passively quenched single photon avalanche diodes: effect of feedback on impact ionization” *2012 Optical Society of America.*

[20]. Mark A. Itzler, Xudong Jiang and Mark Entwistle “Power law temporal dependence of InGaAs/InP SPAD afterpulsing*” Journal of Modern Optics*, Vol. 59, No. 17, 10 October 2012.

[21]. Thomas Frach, *Member, IEEE*, Gordian Prescher, Carsten Degenhardt, Rik de Gruyter, Anja Schmitz, and Rob Ballizany “The Digital Silicon Photomultiplier Principle of Operation and Intrinsic Detector Performance” *IEEE Nuclear Science Symposium Conference Record* 2009.