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Dedy Septono Catur Putranto
Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan

Wei Du
Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan

Hiroaki Satoh
Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan

Atsushi Ono
Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan

Purnomo Sidi Priambodo
Electrical Engineering Department, University of Indonesia, Depok 16424, Indonesia

See next page for additional authors

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Analysis of Hole Lifetime in SOI MOSFET Single-Photon Detector

Dedy Septono Catur Putranto[1,2], Wei Du[1], Hiroaki Satoh[1], Atsushi Ono[1], Purnomo Sidi Priambodo[2], Djoko Hartanto[2], and Hiroshi Inokawa[1*]

1. Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan
2. Electrical Engineering Department, University of Indonesia, Depok 16424, Indonesia

[*]*E-mail: inokawa06@rie.shizuoka.ac.jp*

Abstract

Hole lifetime in the silicon-on-insulator (SOI) metal-oxide-semiconductor field-effect transistor (MOSFET) single-photon detector was evaluated by the analysis of drain current histograms for different light intensities and substrate voltages. It was found that the peaks in the histogram corresponding to the larger number of stored holes grew as the gate bias decreased. This was attributed not to the increased light absorption efficiency or collection efficiency of the photo-generated holes, but to the prolonged hole lifetime presumably caused by the higher transverse electric field inside the body of SOI MOSFET.

Abstrak

Analisis Masa Hidup Lubang pada Pendeteksi Berfoton Tunggal SOI MOSFET. Masa hidup lubang pada detektor berfoton tunggal (*single-photon detector*) transistor efek-medan semikonduktor-metal oksida (*metal-oxide-semiconductor field-effect transistor* atau MOSFET) *silicon-on-insulator* (SOI) dievaluasi dengan menganalisis histogram-histogram arus kering yang dihasilkan dari intensitas cahaya dan voltase substrat yang berbeda-beda. Ditemukan bahwa puncak-puncak pada histogram berkorelasi dengan sejumlah besar lubang tersimpan yang berkembang seiring dengan semakin berkurangnya bias gerbang. Ini disebabkan bukan oleh efisiensi penyerapan cahaya yang meningkat atau efisiensi pengumpulan lubang-lubang yang dipicu cahaya (*photo-generated*), tetapi oleh masa hidup lubang yang menjadi panjang, yang mungkin disebabkan oleh adanya medan listrik melintang di dalam badan alat SOI MOSFET.

Keywords: hole lifetime SOI MOSFET, light absorption efficiency, single-photon detector

1. Introduction

It has been reported that the ordinary silicon-on-insulator (SOI) metal-oxide-semiconductor field-effect transistor (MOSFET) can operate as a single-photon detector, featuring dark counts several orders of magnitude smaller than that of conventional avalanche photodiode (APD), and low operation voltage less than a few volts [1-2]. However, the behavior of the photo-generated holes stored in the body of SOI MOSFET has not been analyzed well. In this paper, we will present the detailed analysis of the drain current histograms under different illumination levels and substrate biases for better understanding of the hole dynamics.

2. Methods

Figure 1 shows (a) the top and (b) cross-sectional views of the device. An 300 nm length n^+ poly-Si-gate (LG) is delineated above 110-nm wide, 50-nm thick silicon channel with p^- dopant consentration less then 10^{15} cm^{-3}. n^+ source/drain region is created in a self-aligned manner using the LG as a implantation mask. Note that this device structure is similar to the one used in the ordinary large-scale integrated circuit, and is much simpler than the previous one [3], [4] in that there is no offset region between LG and n^+ source/drain. Although an upper gate (UG) still exists and hinders the light entrance in the particular design, this can be removed without affecting the MOSFET operation as a single-photon detector. For detection of the stored holes, both the top and bottom channels can be used, but the bottom one, enabled by the biasing condition of $V_{LG}<0$ and $V_{LG}>0$, can be used this time due to the limitation set by the signal-to-noise ratio, as will be explained later. In this case, photo-generated holes are stored under the LG whereas back electron channel is used as an electrometer to detect the presence of the holes. Photo-generation of

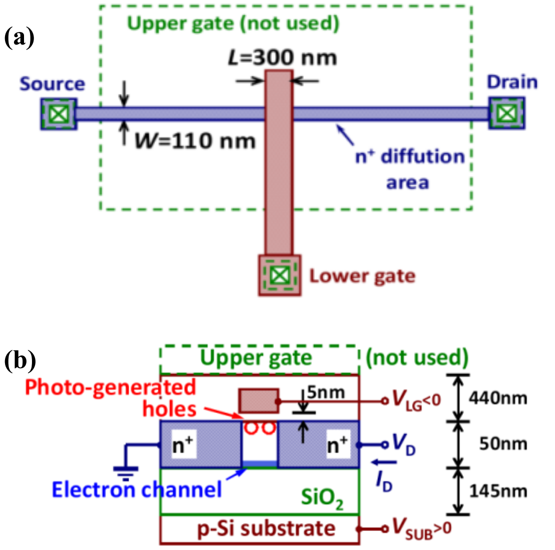

Fig. 1(a). **Device Structure. (a)Top View and (b) Cross-sectional View with Back Channel Operation. Thicknesses of Buried Oxide, SOI, LG Oxide and Insulator Below the UG are 145, 50, 5 and 440 nm, Respectively**

carriers and their recombination will modulate the electron current, and can be observed as pulses.

In the experiment, we changed V_{LG}, and correspondingly adjust V_{SUB} to keep the baseline drain current at the same level of 1 nA. For different V_{LG}, we evaluated the hole lifetime by analysis of the drain current histogram.

3. Results and Discussion

Figure 2 shows the I_D-V_{LG} curves for different V_{SUB} from -10 to 10 V. As we mentioned, the operating condition is located where $V_{LG}<0$ and $V_{SUB}>0$ and electrons flow in the bottom channel, considering the low noise level in $-5 < V_{SUB} < 1$ V, as shown in Fig. 3, and the high optical response for $V_{SUB} > 0$.

Figure 4 shows typical drain current waveforms for different intensity levels at wavelength of 550 nm at 300 K. We shift each waveform for clarity. It shows that pulse count increases as the light intensity increases. Moreover, discrete current levels can be seen clearly, corresponding to the different number of holes stored under the lower gate. Figures 5(a) – (f) are histograms of drain currents corresponding to Fig.4. The closed symbols are obtained data and solid lines are fitting curves with Gaussian distribution. The peaks from left to right correspond to the number of stored holes of 0, 1, 2, 3 and 4. When incident light intensity increases, more and more holes are generated. Thus, the possibility of holes being stored under the LG increases, resulting in higher peaks for more stored holes.

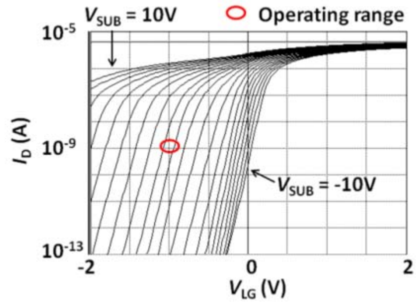

Fig. 2. **I_D-V_{LG} Curve with V_{SUB} as a Parameter. We Use Bottom Electron Channel and Photo-generated Holes are Stored Below the LG. Drain Voltage V_D is Kept at 50 mV**

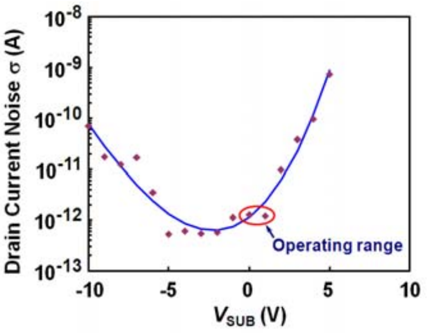

Fig. 3. **Noise Evaluation in Dark Condition. σ is the Standard Deviation of the Drain Current for the Bandwidth of 5 Hz. V_{LG} is Adjusted to Keep the Average Drain Current of 1 nA**

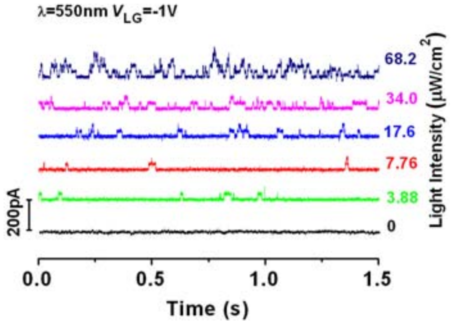

Fig. 4. **Drain Current Waveforms at 300 K for Different Levels of Light Intensity at the Wavelength of 550 nm. Baseline Current is Adjusted to 1 nA by V_{SUB}, and each Waveform is Shifted for Clarity. V_D and V_{LG}, are 0.05 and -1 V, Respectively**

Figure 6(a) shows probabilities of states f_i corresponding to the number of stored holes i as a function of count rate, namely, hole generation rate R. The behavior can be explained by the state transition diagram in Fig. 6(b). The theorical curves (solid curve) are derived from the rate equations under steady-state condition, $f_i/\tau_i=f_{i-1}R$ and $\sum f_i=1$, where τ_i is the hole lifetime for the number of stored holes of i (=0, 1, 2, 3 and 4) [4].

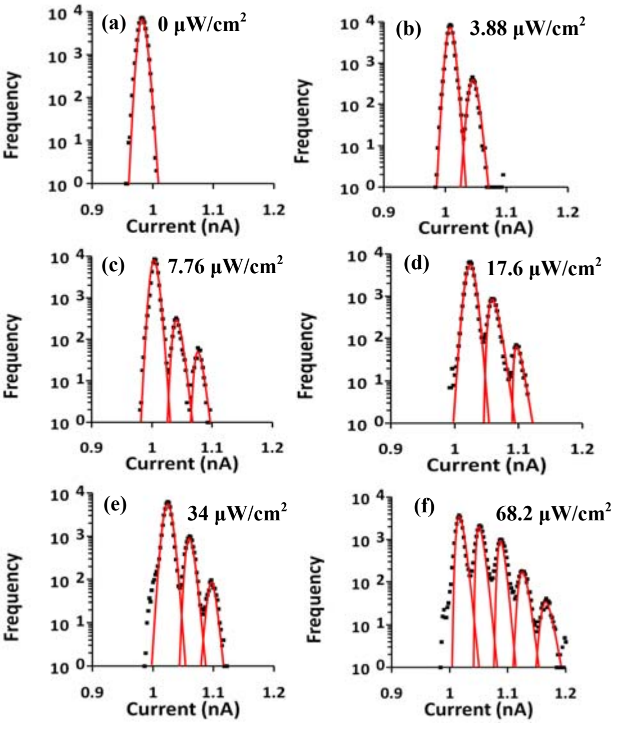

Fig. 5. Histograms of Digitized Drain Current Corresponding to Fig. 4. The First, Second, Third and Fourth Peaks from Left in Each Graph Correspond to Zero, One, Two, Three Stored Holes, Respectively. Data Acquisition Time Period and Time Step Are 2.45 s and 49 μs, Respectively, and 50000 (=2.45s/49 μs) Data Points (Currents Values) are Classified into Bins with a Width of 2 pA

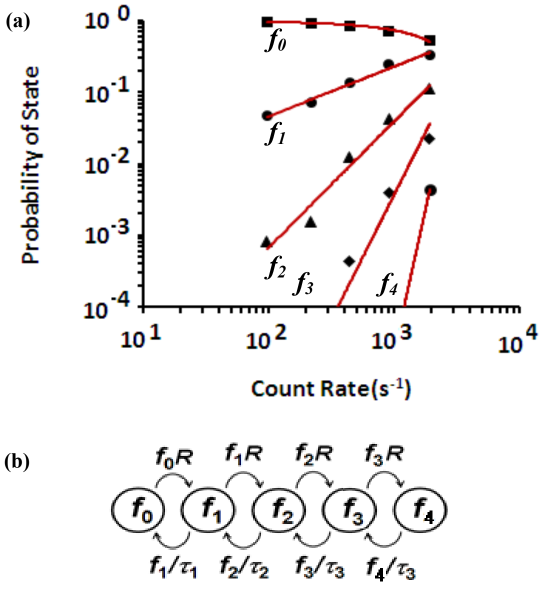

Fig. 6. (a). Probability of States Obtained from Fig. 5 as a Function of Count Rate, Namely, Hole Generation Rate R. State f_0, f_1, f_2, and f_3 Correspond to Zero, One, Two and Three Stored Holes, Respectively. (b) State Transition Diagram to Explain (a)

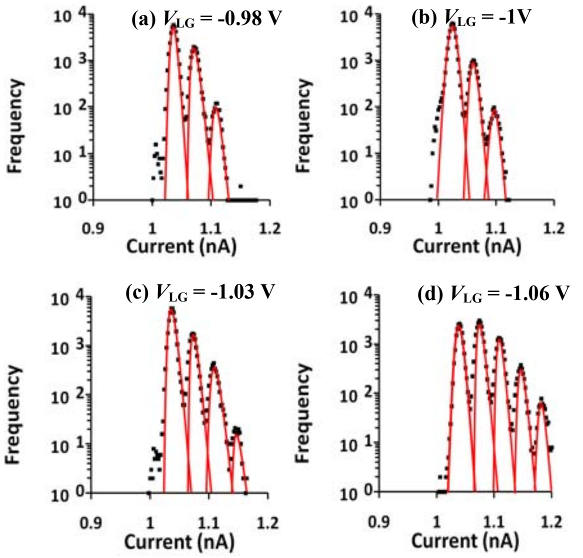

Fig. 7. Histograms of Drain Current for (a) V_{LG} = -0.98 V, (b) V_{LG} = -1.00 V, (c) V_{LG} = -1.03 V, and (d) V_{LG} = -1.06 V with Different V_{SUB} to Keep the Baseline Drain Current at the Same Level of 1 nA Under the Continuous Light Illumination of 34 μW/cm². The First, Second, Third, and Fourth Peaks Correspond to the Number Stored Holes of 0, 1, 2, and 3, Respectively

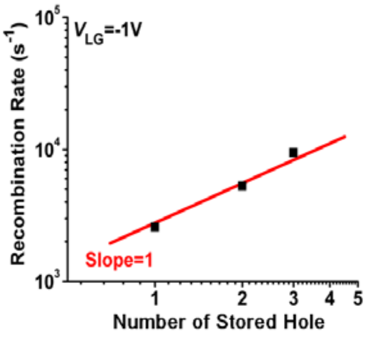

Fig. 8. Hole Recombination Rate as a Function of Number of Stored Holes at V_{LG}= -1 V. The Data are Derived from the Analysis of the Drain Current Histograms. Slope of the Fitting Line is One

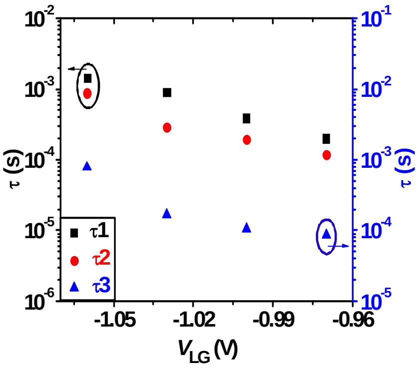

Fig. 9. Hole Lifetime as a Function of V_{LG}. τ_1, τ_2 and τ_3 are the Lifetimes when the Number of the Stored Holes are One, Two and Three, Respectively

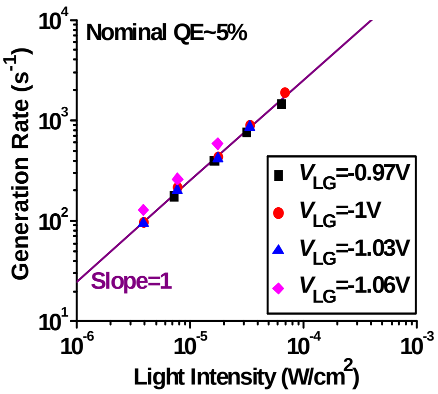

Fig. 10. Hole Generation Rate as a Function of Incident Light Intensity for Each Bias Condition. Slope of the Fitting Line is One

Figure 7 shows the histograms of drain current for (a) V_{LG} =-0.98 V, (b) V_{LG} =-1.00 V, (c) V_{LG} =-1.03 V, and (d) V_{LG} = -1.06 V with different V_{SUB} to keep the baseline drain current at the same level of 1 nA. The closed symbols are obtained data and solid lines are fitting curves with Gaussian distribution. The peaks from left to right correspond to the number of stored holes of 0, 1, 2 and 3. It can be seen that the peaks in the histogram corresponding to the larger number of stored holes become higher as the V_{LG} decreases. This may be caused by the longer hole lifetime, higher light absorption efficiency, or higher collection efficiency of the photo-generated holes.

Figure 8 shows the recombination rate (inverse of the lifetime) as a function of number of stored holes at V_{LG}=-1 V. Recombination rate is proportional to the number of stored holes. In other V_{LG} cases (V_{LG}=-0.97, -1.03, and -1.06 V) we have measured, the results show very similar tendency, although some data points a little deviate from the proportionality mainly due to statistical error for larger *i*.

The hole lifetime at different V_{LG} are depicted in Figure 9. The hole lifetime increases significantly as V_{LG} decreases. It is estimated that lower V_{LG} (higher transverse electric field) separates the stored hole and electron more effectively, and reduces the probability of recombination, leading to the longer lifetime.

For the application to the single-photon detection [4], quantum efficiency (QE) of the hole generation is important. As shown in Fig. 10, there is proportionality between hole generation rate and incident light intensity, and the nominal QE, assuming the photosensitive area of 300 × 110 nm^2, is almost independent of the V_{LG}, indicating that light absorption and hole collection efficiencies are not much affected by the bias condition. This also means that the hole lifetime can be controlled without affecting the QE.

4. Conclusions

The drain current histograms of the SOI MOSFET single-photon detectors were analyzed under different light intensities and substrate voltages. It was found that the peaks in the histogram corresponding to the larger number of stored holes became higher as the substrate bias decreased. This was attributed to the prolonged hole lifetimes presumably caused by the higher electric field inside the body of SOI MOSFET. The possible control of the hole lifetime is of great use in high-speed operation of this unique single-photon detector.

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