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Low Dimensional Ge Island on Si for Visible Metal-Semiconductor-Metal Photodetector

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ABSTRACT

In this work, a study of low dimensional germanium (Ge) island on silicon substrate (Si) for visible metal semiconductor metal (MSM) photodetector was presented. The study was carried out using Silvaco ATLAS device simulator. Three Ge islands were designed such as big Ge, small Ge and combination Ge. Bulk Ge is also added for comparison. The structure of the island was constructed at the beginning of Atlas simulation and continued for simulation of MSM photodetector. From the structure, the energy band gap of the material was extracted whereby altering the Ge island sizes has altered the energy bands. The performance of the Ge island on Si as MSM photo detector was evaluated by dark and photo current – voltage (I-V) characteristics. It was found that the Ge island on Si significantly enhanced the current gain (8 times) compared to the bulk Ge. The combination Ge island MSM photo detector exhibited the highest gain and response towards visible light among the three islands.

Keywords: *Ge island; Shottky barrier height; ideality factor; energy band gap; photo current; dark currents.*

1. INTRODUCTION

The progress of high frequency heterojunction bipolar transistor has sparked the interest in the growth of the Ge on Si [1]. This was motivated by the confinement of charge carrier in low dimensional Ge on Si. The compatibility of the Ge integration with existing Si technology as well as possibility of incorporation of its low dimensional structure facilitated intense research in this area. Ge is indirect semiconductor with high electron and hole mobilies. Making Ge in nanoscale has increase the band gap (change to direct semiconductor) and exhibited unique optical properties [2]. Experimentally, Ge nanostructures on Si are grown mostly by sophisticated molecular beam epitaxy [3, 4] or by chemical vapor deposition[5] techniques. Through the use of these techniques, the size of the island can be precisely controlled to provide size quantization effect at low temperature and at room temperature [6]. Studies have been performed to identify the optimum growth temperature [7] and the evolution of the Ge island with in situ post-growth annealing [8]. However, these methods still rely on expensive growth apparatus. Alternatively, Baharin and Hashim [9] have shown a possible way of growing Ge islands using low cost methods of thermal evaporator and rapid thermal

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annealing (RTA). However, the challenge in this technique is to control the size and position of the Ge islands because of the non-epitaxial nature of the deposited Ge layers. Nonetheless, the non-uniform Ge islands beneath the Ni contact on the Si substrate have been shown to suppress the dark current and enhance the photocurrent of the metal–semiconductor–metal photodetector. In addition, Abd Rahim et. al [10] has shown that uniform Ge island on Si with enhanced photodetection at visible region can be obtain by RF Sputtering and RTA process.

This has motivated the needs of the Ge island on Si to be simulated to see its optical performance towards the visible spectrum. Silvaco is an attractive comprehensive TCAD tool which capable for simulating the fabrication and characteristic of the semiconductor device. By simulation, the time for fabrication can be reduced and the optimum Ge growth condition can be obtained while the expected performance of the device can be foresee. In this work, various sizes of Ge islands on Si substrate were simulated using Silvaco ATLAS simulator. As deposited Ge or Ge bulk was also included for comparison. The structures were subsequently tested for visible MSM photodetector. Finally, the structural and I-V characteristic of Ge islands on Si MSM photo detector were analyzed.

2. METHODOLOGY

Simulation of Ge bulk and Ge islands were performed using Silvaco TCAD tool. There are three types of Ge islands constructed which is small Ge(0.1 µm width), big Ge (0.5 µm) and combination Ge (0.1 µm and 0.5 µm) as shown in Table 1.

Table 1: Size Specification for Ge Island on Si

Structure	Ge island width(µm)
Bulk Ge	12
Big Ge	0.5
Small Ge	0.1
Combination Ge	0.5 & 0.1

Figure 1 shows the flow chart of the steps undertaken in simulating the structures. The process started with input file written for the three structures, followed by simulating the structures and analyzing the results of the simulation.

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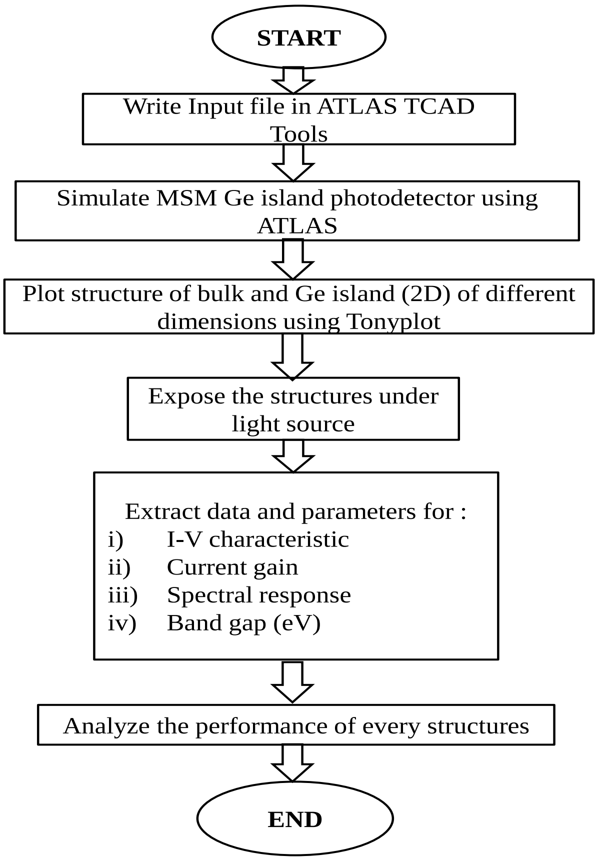

Figure 1: Flowchart for Overall Investigation and Simulation in ATLAS Silvaco TCAD Tools.

In the first part of the simulation, the Si wafers were initialized and the mesh was defined by setting the x- and y-mesh. The fine mesh was defined at the islands and wetting layer regions whereas coarse mesh was tabulated around the substrate as shown in Figure 2.

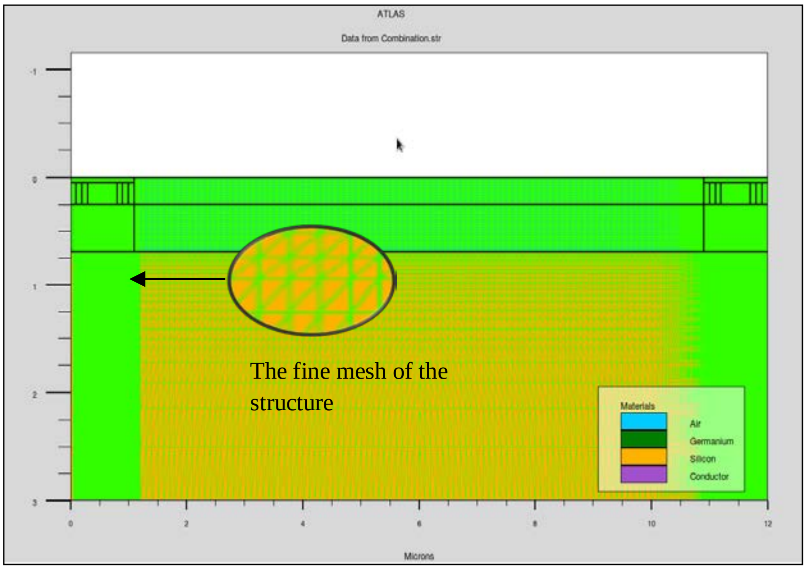

Figure 2: Example Fine Mesh for Combination Structure

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This was done to ensure the subsequent device characteristics will be simulated accurately. After that, the construction of the Ge islands and the MSM photodetector were develop by setting the region and contact statements where as region num=12, x.min=8.8, x.max=9.3, y.min=0.1, y.max=0.3, material=germanium, electr name=cathode, x.min=8.80, x.max=9.30 and y.min=0.1.

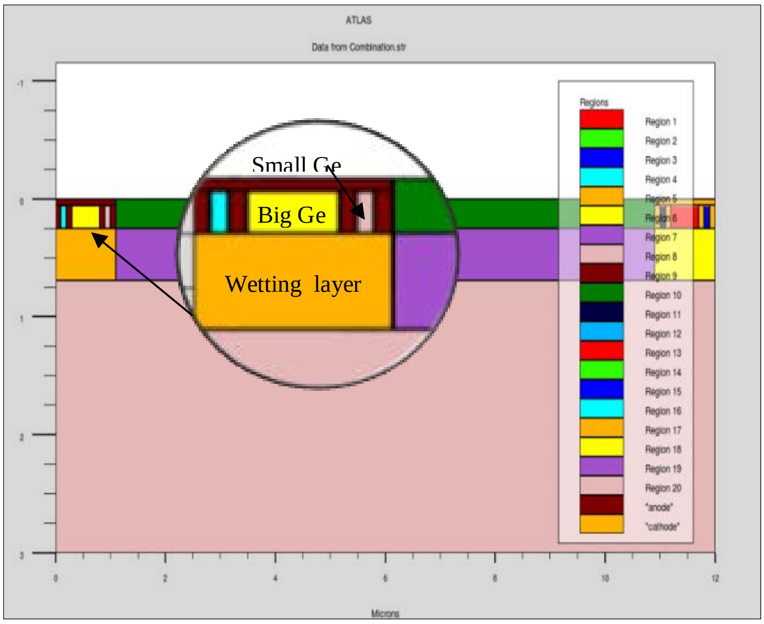

Figure 3: The Final Structure for Combination Ge After Region Statement

Figure 3 shows the final structure after the regions and electrode were defined. The statements used in the simulation of the structure and its device characteristics were defined by following the order stated in Table 2.

Table 2: ATLAS Command Groups with the Primary Statement in Each Group.

Group	Statements
Structure Specification	Mesh, Region, Electrode, Doping
Material Model Specification	Material, Models, Contact, Interface
Numerical Method Selection	Method
Solution Specification	Log ,Solve, Load, Save
Result analysis	Extract, Tonyplot

Nickel (Ni) contact has been used by defining the work function of 5.01 eV. Nickel was chosen for the contact to obtain Schottky behavior for the photodetector. To evaluate the photodetection of the structures, the light source was shined to the sample by defining the beam power and its respective wavelength. This was done after the model and contact statements were generated. Finally, the I-V characteristics were simulated by the numerical method selection and solution specification as following:

solve b1=750 vanode=0.5 vstep=0.1 vfinal=5.0 name=anode

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The photodetectors were biased from 0.5 until 5 V under dark and light illuminated. The obtained I-V characteristics were analyzed and compared with the bulk Ge device. Figure 4 shows the light source (beam) that has been applied to the completed structure.

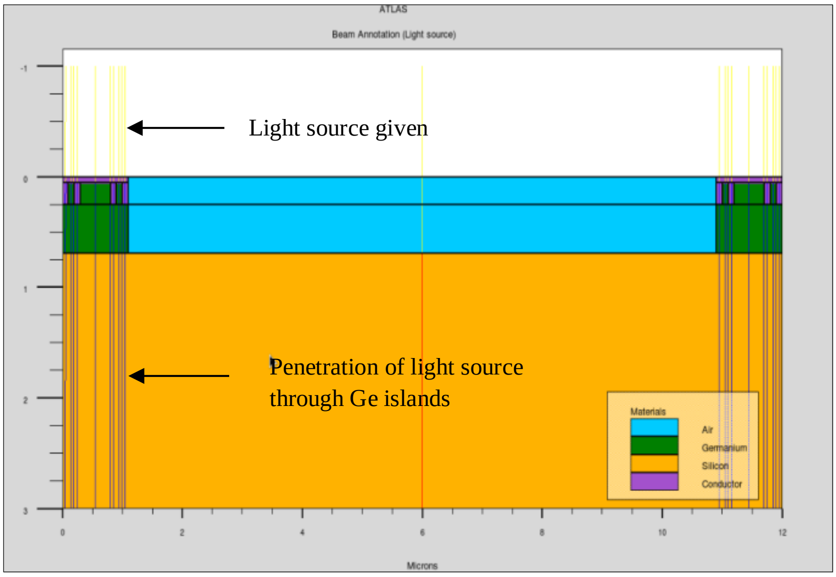
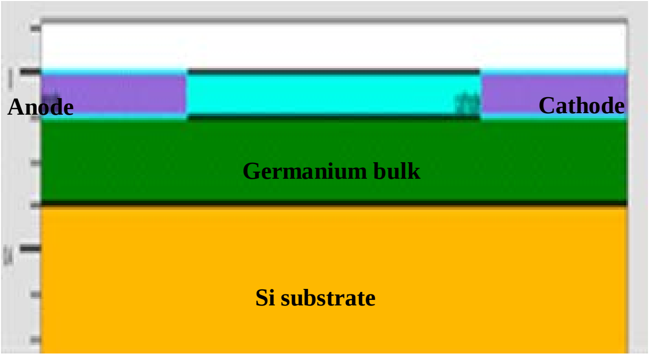


Figure 4: Ilumination of Light Source to the Ge Island on Si MSM Photodetector

3. RESULTS AND DISCUSSION

Figure 5(a)-(d) presents the final structure of the bulk Ge, big Ge, small Ge and combination Ge respectively. The Ge islands were identified by the region on dark green color.

a) Bulk Germanium



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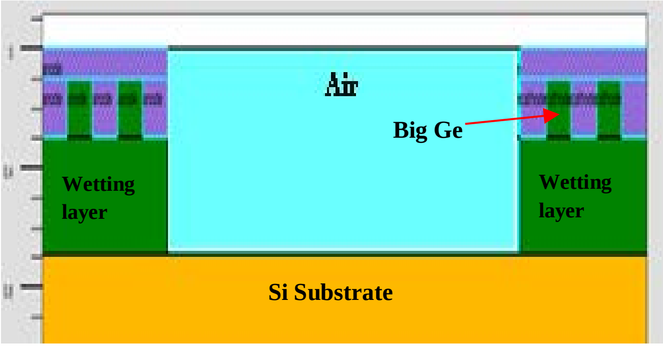
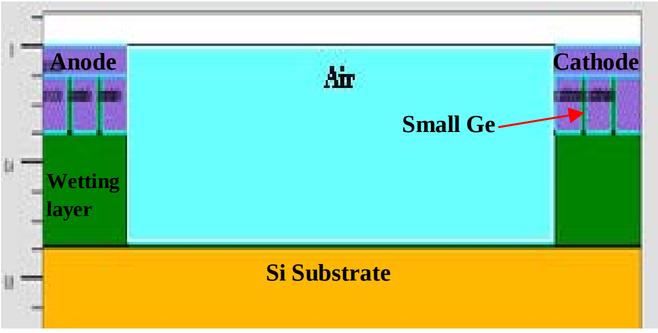
b) Big Germanium



c) Small Germanium



d) Combination Germanium

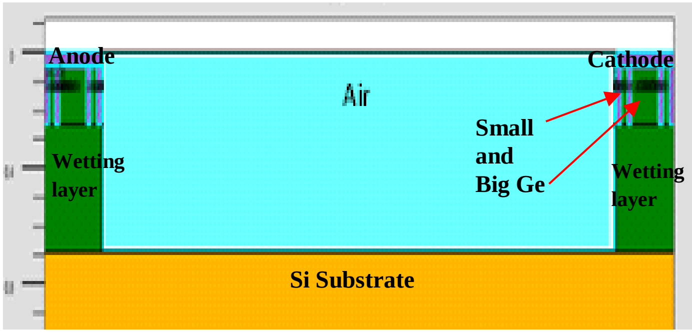


Figure 5: Final Structures for a) Bulk, b) Big, c) Small and d) Combination Ge on Silicon Substrate

Figure 6(a)-(d) shows the extracted energy band gap of the Ge islands on Si for the three dimensions of Ge and bulk Ge. It can be seen that by altering the Ge sizes has caused the changes in the energy band gap of the structures. Specifically the band gap increases as the island size decreases. This agreed with the quantum confinement effect which stated that decreasing crystallite size will increase the band gap [11]. Combining the islands sizes exhibited the highest Eg which probably due to the combination effect of the small and big island underneath the Ni contact. All the Ge islands on Si samples show a change from indirect semiconductor to direct semiconductor indicated by the increase in their energy band gap. This shows their potential for visible spectrum photodetection. In addition, large band gap also leads to enhance photon absorption.

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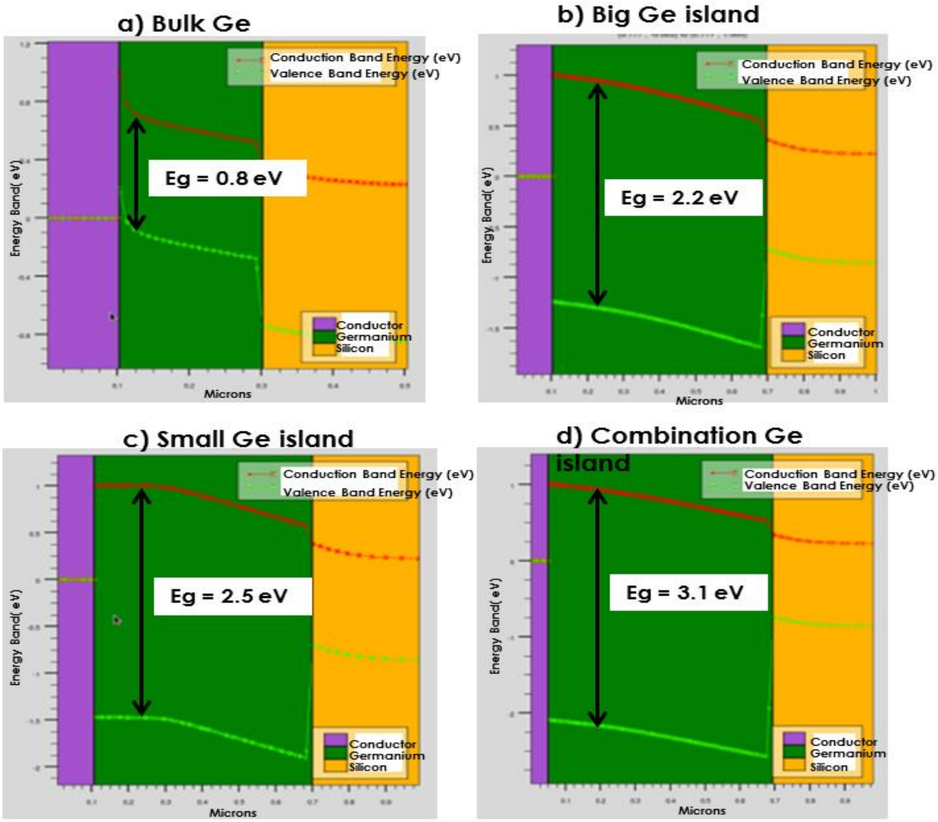

Figure 6: Energy Band Gap for a) Bulk, b) Big, c) Small and d) Combination Ge Islands on Silicon Substrate

To examine the potential of the structures for photonic applications, the metal finger contacts were deposited on the Ge islands to form metal-Ge islands-metal photodetector.

Figure 7 shows the current-voltage (I-V) characteristics of the MSM photodetectors measured in the dark (Id) and under illumination (Ip) for the three Ge island samples. For comparison, the As-deposited sample which is the bulk Ge was also included. The current of the Ge island MSM photodetector increased with the bias voltage and saturated gradually as the voltage beyond 1V. The combination Ge sample exhibited the lowest dark current followed by small Ge and big Ge respectively. Interestingly, the dark current were decreased by a factor of 1.12 and 1.94 compared to small Ge and big Ge value respectively. This is probably due to the increase in resistivity of the rougher surface for combination Ge islands compared to smoother surfaces of small and big Ge islands. Upon photons illumination, all the Ge islands showed tremendous response, producing significant free carriers for enhanced current conduction. The combination Ge islands produced the highest photo current compared to small and big Ge by a factor of 1.1 and 1.23 respectively at 5 V bias. While the bulk Ge sample showed insignificant different between photo and dark currents respectively.

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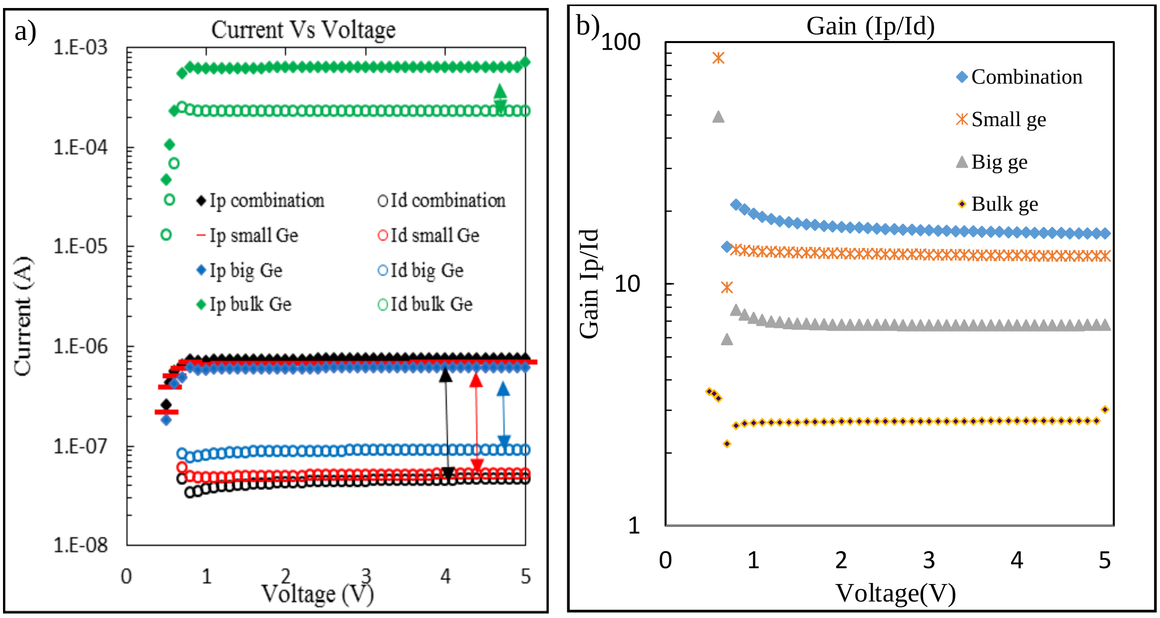

Figure 7: (a) Current-Voltage Characteristics and (b) Current Gain(Ip/Id) for the Three Ge Island Samples in Comparison to Bulk Ge

The evaluation of the performance for photodetector is probed by measuring the current gain. Current gain is the ratio of the photo current- to-dark current. Figure 7 b shows current gain for the three Ge island devices along with the bulk Ge device.

Interestingly, all the Ge island devices showed enhanced current gain compared to bulk Ge device. The significant enhancement of the photo currents from the Ge island samples were attributed to the optical phonon confinement of the low dimensional Ge and the higher Ge mobility.

To examine the performance of MSM photodetector, Schottky barrier height was extracted which will probe the quality of the Schottky contacts on the Ge islands. The performance and reliability of a Schottky contact is determined by the quality of the interface between the deposited metal (Ni)and the semiconductor surface (Ge island) and the nature of the current transport across this interface The thermionic emission theory is the well-known model used to study the forward I-V characteristics of a Schottky diode.

According to this theory, the diode current, I_d is described by the following equation:

$$I_d = I_0 \exp\left(\frac{qV_d}{nkT}\right)\left[1 - \exp\left(\frac{-qV_d}{kT}\right)\right] \tag{1}$$

where Vd is the voltage across the diode, n is the ideality factor (which may depend on temperature and independent on voltage), *k* is the Boltzman constant, and Io is the saturation current given by:

$$I_0 = AA^{**}T^2 \exp\left[\frac{-q\varphi_B}{kT}\right] \tag{2}$$

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where q is the electron charge, T is the temperature, A is the contact area, A** is the effective Richardson constant and φ_B is the Schottky barrier height. The saturation current, Io is mainly determined by the barrier height φ_B and the effective Richardson constant *A***. Equation (1) at V>3kT/q, can be simplified to:

$$I_d = I_0 \exp\left(\frac{qV_d}{nkT}\right) \tag{3}$$

Table 3: Data Extracted from (I-V) Graph. The SBH and Ideality Factor were Extracted under Dark Current Condition

Sample	SBH in Dark (eV)	IdealityFactor (n)	Id at 5V (A)	Ip at 5V (A)	Rs (MΩ)	Gain at 5v
Bulk	0.845	2.73	2.32E-4	6.31E-4	0.022	2.73
Big Ge	1.199	1.78	9.03E-8	6.11E-7	55.37	6.77
Small Ge	1.217	1.73	5.22E-8	6.81E-7	95.78	13.04
Combination Ge	1.226	1.69	4.66E-8	7.52E-7	107.29	16.15

The theoretical value of *A*** can be calculated using $A^{**} = 4\pi m^* qk^2/h^3$. The plot of ln I_d vs V_d will give a straight line with a slope of $q/(nkT)$, and the intercept with y-axis will yield I_o, in which Schottky barrier height, φ_B can be obtained using Eq. *(2)* and the ideality factor can be extracted from the slope. The Schottky barrier height and the ideality factor for the Ge island on Si samples were listed as in Table 3. It was observed that the combination Ge island exhibited the lowest ideality factor (1.69) and the highest Schottky barrier height (1.226 eV). The lowest dark current in the combination Ge island could be attributed to the high barrier height of the metal contact. On the other hand, the Schottky barrier heights of the Ge islands were seen to increase and the ideality factors were decrease with decreasing of islands sizes. The observations have been ascribed to barrier inhomogeneities from the metal semiconductor interface. In spite of this, the lower ideality factors indicate the better quality of the Schottky's contacts under investigation for the Ge island device compared to bulk Ge.

Figure 8, shows spectral response of the three Ge islands and Ge bulk from deep UV and infrared regions. Generally, all the Ge islands exhibited significant response towards green and violet regions. Specifically, big Ge showed peak current at 550nm (Eg=2.2 eV) and small Ge at 500nm (Eg=2.5 eV) respectively. While combination Ge responsed at 400nm (Eg=3.1eV). This shows an agreement with the band gap changes shown in Figure 6. The combination Ge depicted the highest current response towards light at violet region. Therefore, this shows the potential of the Ge Island on Si devices for photodetection at visible (from UV to green) spectrum. The bulk Ge shows no response over the visible spectrum.

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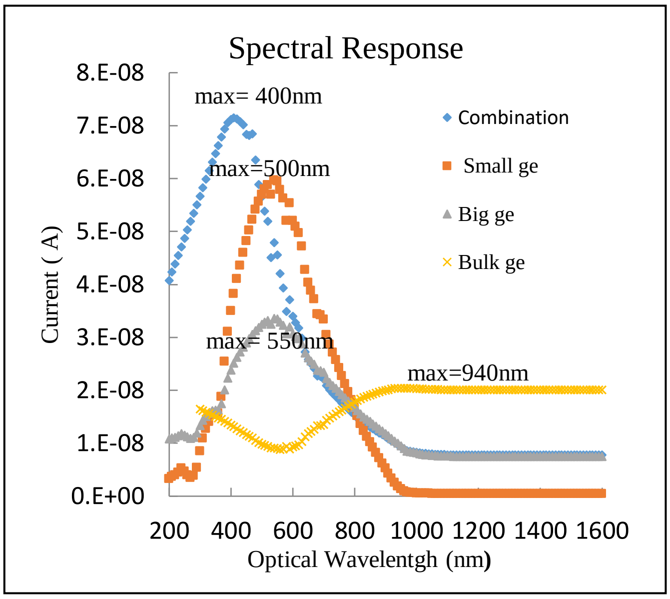

Figure 8: Spectral Response of the Three Ge Islands and Ge Bulk from Deep UV until Far Infrared Regions

4. CONCLUSION

In conclusion, different Ge islands on Si substrate have been successfully simulated using Silvaco TCAD Tools. The result shows that the energy band gap increases as the Ge islands size decreases which is believed to be due to the quantum confinement effect of the low dimensional structure. By combining small and big Ge, the photoresponse have been further enhanced. A visible broadband photoemission and detection was observed from UV to green with blue-shift for Ge island on Si compared to bulk Ge.

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