Fast, High-efficiency Germanium Quantum Dot Photodetectors

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Abstract— **We present on high efficiency metal-insulator-semiconductor (MIS) photodetectors based on amorphous germanium quantum dots (QDs) embedded in a SiO_2 matrix. High internal quantum efficiencies (IQE) were achieved across a broad wavelength range, with peak value reaching 700% at -10 V applied bias due to high internal photoconductive gain. The transient photoresponse behavior is also studied and it was found that the response time of the photodetector depends on the thickness of the QD layer. We also discuss the conduction mechanism which leads to the high photoconductive gain.**

***Index Terms*—Germanium, quantum dots, photodetector.**

I. INTRODUCTION

Recently, there have been a lot of efforts to incorporate group IV semiconductor Quantum Dots (QDs) into existing optoelectronic and photovoltaic applications. In particular, Si and Ge QDs have shown promise in improving the figures of merit in photodetctors. Si QD-based photodetectors have exhibited efficiency values as high as 200% in the visible range [1, 2]. However, Ge QD-based devices show even more promise: SiO_2-encapsulated Ge QDs can be easily fabricated at low temperatures [3, 4] and have higher absorption coefficients due to localized defect states at the Ge / SiO_2 interface [5, 6] So far, the maximum responsivity values reported for Ge QD photodetector has been 0.13 A/W at λ = 820 nm [7], and 1.8 A/W at λ = 600 nm [8](devices in the latter were fabricated through a high-temperature annealing procedure).

In this report we present on high efficiency metal-insulator-semiconductor (MIS) photodetectors based on amorphous Ge (a-Ge) quantum dots embedded in a SiO_2 matrix. We study its photoresponse efficiencies (with peak internal quantum efficiency of up to 700%) and its transient response behavior (as fast as 40ns). We also discuss the photoconductive gain mechanism in the device.

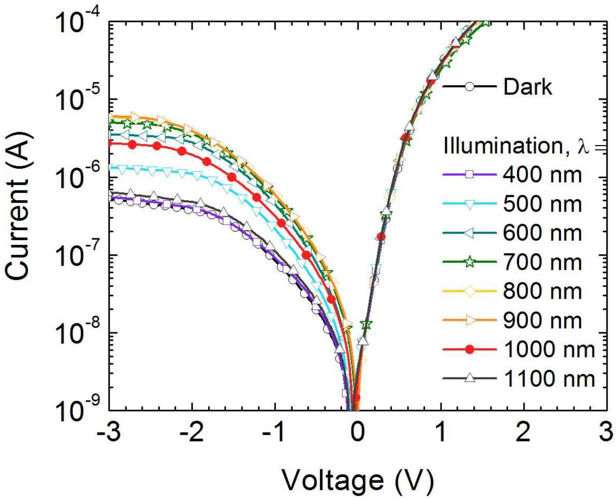

Fig.1 The Ge QD photodetector *I(V)* characteristics as a function of excitation wavelength in the range of 400–1100 nm [9].

II. FABRICATION AND EXPERIMENTS

The fabrication of Ge-rich SiO_2 films was done by rf-magnetron co-sputtering deposition of a SiO_2 and a Ge target onto a (100) n-Si substrate maintained at 400°C. The process naturally forms a-Ge QDs embedded in a SiO_2 matrix, with the QDs mean size of 2-3 nm. Different thicknesses of QDs layer can be achieved by etching the QDs films in HF solution. Reflectance and ellipsometry measurements were performed to determine the final thicknesses of these films. The top contact of the MIS structure was later fabricated by sputtering a fully transparent indium-zinc-oxide (IZO) film on the top of the

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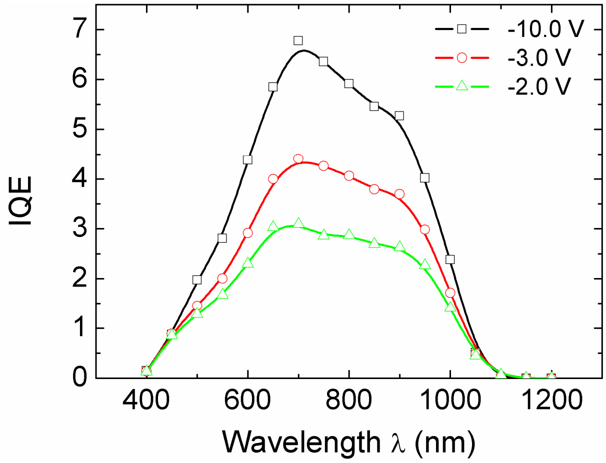

Fig.2 Internal quantum efficiency (IQE) as a function of wavelength under different reverse bias values [9]

QD layer. The bottom contact was made to the n-Si substrate using silver paste [9].

To characterize this device, optical and electrical measurements were performed. Reflection (used to obtain the internal quantum efficiency [IQE]) was studied in the λ = 400–1100 nm wavelength range. Current-voltage *I(V)* curves were measured with an Agilent 4155C parameter analyzer under illumination (same wavelength range). Internal quantum efficiency (IQE) was later extracted from these measurement results. To study time response, we have connected a load resistor in series with the device, and taken signal from the resistor through an oscilloscope.

III. RESULTS AND DISCUSSION

We first carried out *I(V)* measurements under constant illumination conditions at various incident wavelengths (400–1100nm), as reported in Fig. 1. Absolute values of currents were taken in order to make the log-plot. The device exhibits significant photoresponse across a range of 500–1000 nm when compared to dark condition. Additionally, a reference device with the same thickness of SiO_2 but without a-Ge QDs was also fabricated. This device exhibited no photoresponse at any wavelength, which clearly shows that the Ge QDs are necessary for the device to function

To understand the underlying physics behind the carrier generation process, IQE was also studied, as it specifies how effectively each absorbed photon can create free charge carriers. The IQE was calculated by measuring the reflectance *R* at normal incidence, then normalizing the number of photogenerated carriers by the number of absorbed photons (i.e., by (1 – *R*) times the number of incident photons), as a function of λ. We summarized the results in Fig. 2, which shows photogeneration gain existing over a broad wavelength range and at a bias as low as –2 V. The peak IQE observed is as high as 700% at –10 V applied bias and at $\lambda \sim 700$ nm, due to the fact that seven current carriers are able to be generated due to one absorbed incident photon.

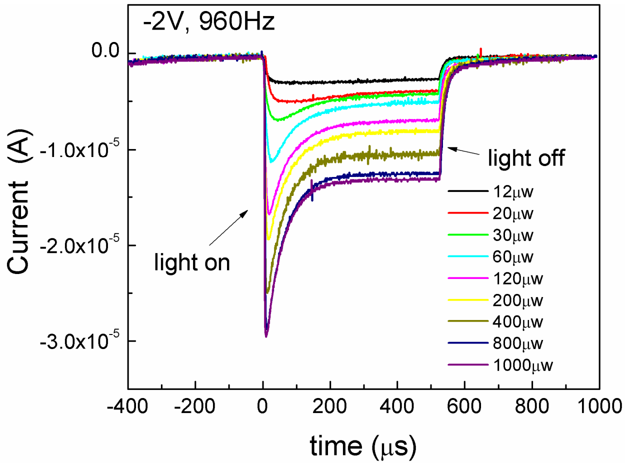

Fig.3 Experimental photocurrent response to light pulses at constant *V* = –2 V and for various optical powers.

To further understand the behavior of the device, we perform transient photoresponse experiments. The QD photodetector was illuminated with a laser beam (λ = 670 nm) chopped at 960 Hz via a mechanical chopper. The voltage applied was –2 V, with a series load resistor of 20 kΩ for signal output. The results are summarized in Fig. 3. The nature of the transient photoresponse depends on the incident power (*P*): as *P* increases, a current overshoot start to appear, wherein the current exceeds the equilibrium value for a short period of time before slowly decaying to the steady state. This suggests the possibility of charge redistribution across the QD layer in the device. As the incident power increases, more and more charge will accumulate in the QD layer thus reducing the effective field across it, therefore leading to a reduction of photocurrent after initial overshoot.

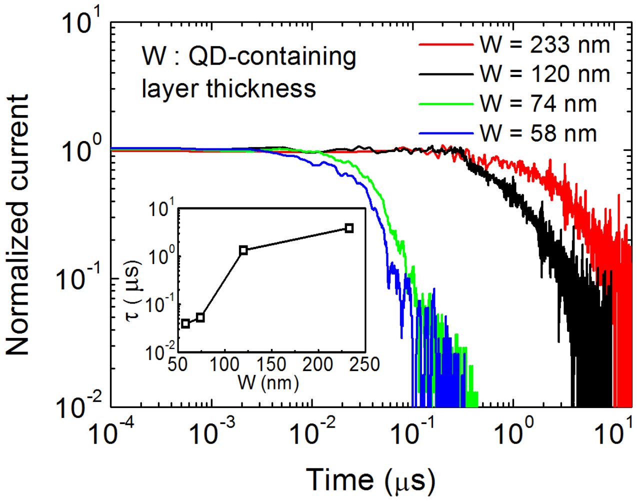

Fig.4 Response time τ under electronically modulated light signal as a function of QD-containing layer thickness *W*, inset shows the response time τ *vs. W*.

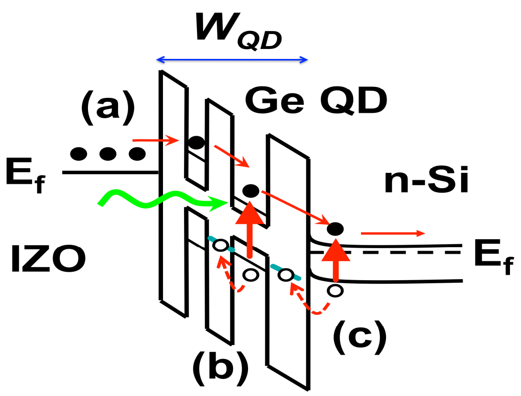

Fig.5 Transport processes under reverse bias and illumination in the device, where W_{QD} represents the Ge QDs film thickness: (a) electron injection from IZO layer; (b) photon absorption in Ge QDs and slow tunneling transport of holes between contiguous QDs; (c) photon absorption in silicon substrate.

Another aspect to consider when characterizing a photodetector is its response time τ (defined here as the time it takes for the device to reach dark condition when illumination is turned off). We attribute the major time delay in the device to be the carrier hopping time through the QD layer. Therefore, by reducing the QD layer thickness, we would expect faster response time for the device. We thus carried out the response time measurement for devices of different QD layer thicknesses. As discussed before, these devices were made by etching the initial sample to different thicknesses with HF solution. The measurements were performed using a fast modulation laser as incoming beam, with circuit setup similar as before, except here we use a 50 Ω load resistor to reduce the *RC* delay. The results are shown in Fig. 4. Indeed, we have achieved faster response speed by decreasing the QD layer thicknesses as shown. For QD layer thickness W= 58 nm, we are able to achieve a response time as fast as 40 ns. In the inset of Fig. 4, we also plot the relation between response time and QD layer thickness. We noticed the response time tends to reach a limit value for small thicknesses, suggesting a possible limitation from parasitic capacitance.

Finally, we would like to discuss in detail the conduction mechanism in the device. Because V drops over the thick insulating layer and we observe photoconductive gain as low as –2 V, we can rule out impact ionization in the Ge QDs or the substrate as the dominant gain mechanism. Instead, an intuitive description of photoconductive gain is reported in Fig. 5 (under reverse bias): in the absence of excited quantum dots (light "off"), electrons tunnel from the IZO into the QDs in the thick oxide layer and then traverse the thick oxide via inter-QD hopping – process (a) in Fig. 5. Upon illumination (light "on") electrons and holes are generated in the QDs and in the Si substrate – processes (b) and (c) respectively in Fig. 5. Both electrons and holes move via inter-QD hopping, but the electrons are much more mobile, due to their lower effective mass. The positively charged holes lag behind, generating a dynamically "trapped" positive charge that enhances the electron injection, increasing the rate of process (a) and leading to photoconductive gain. A similar gain mechanism was suggested previously for photoconductive gain in QD-containing MIS structures (where holes are trapped by Ge QDs) [7].

IV. CONCLUSION

In conclusion, we have demonstrated the high efficiency photodetector based on MIS structure containing a-Ge QDs in the SiO_2 matrix. The Ge QD photodetector exhibits photoresponse across a wide spectrum, covering the visible to near-infrared range, with IQE values as high as 700% , and also a fast response time of ~ 40 ns. Meanwhile, the ease of fabrication and low processing temperature make it compatible with standard CMOS process.

ACKNOWLEDGMENT

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