Metal-Semiconductor-Metal Ultraviolet Detectors Utilizing Ge Nanocrystals Active Medium on Si Substrate

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ABSTRACT

Metal-Semiconductor-Metal (MSM) ultraviolet (UV) detectors utilizing Ge nanocrystals embedded in SiO_2 matrix as active medium on Si substrate had been demonstrated. The Ge nanocrystals with size ranging from 20 to 40 nm and an average density of 1.91×10^{11} cm^{-2} were formed by selective oxidation of hydrogenated amorphous SiGe/Si (a-SiGe:H/a-Si:H) multilayers. An UV luminescence peaking at 391 nm (3.17 eV) for the obtained Ge nanocrystals active medium was observed with a cathodoluminescence spectroscopy. Based on this active medium, the responsivity, photo-current, and dark-current of fabricated MSM UV detectors were 0.0086 (A/W), 125 μA, and 4.78 nA, respectively, and the device photo-to-dark current ratio could reach 2.6×10^4.

Keywords: metal-semiconductor-metal, ultraviolet, detector, ge, nanocrystals

1 INTRODUCTION

In the past decade, much effort has devoted to transmitters, detectors, or filters that are efficient and compatible to existing well-established Si-based integrated circuit (IC) technology [1-3]. Especially, many researches had focused on semiconductor-based ultraviolet (UV) detectors. These devices have a significant commercial and scientific interest for solar UV monitoring, astronomy, lithography aligners or secure space-to-space communications. Mostly, current UV technology utilizes wide-bandgap Ⅲ-Ⅴ compound materials, such as nitrides [4, 5]. Other novel approaches include the use of organics and phosphors. Silicon-based UV detection usually utilizes silicon carbide materials and amorphous silicon alloys [6, 7]. Since the observation of the efficient photoluminescence from porous Si [8], nano-meter scale group Ⅳ semiconductor Si and Ge structures have extensively been studied because it would open a new possibility for indirect-gap semiconductors as new materials for optoelectronic applications. Nayfeh et al. presented UV detectors created by deposition of Si nanoparticles active medium on Si substrates [9]. Besides, luminescent Ge nanocrystals have been fabricated by several methods such as rf cosputtering, ion implantation with subsequent annealing, and oxidation of SiGe alloys [10-12]. An UV (3.1 eV) photoluminescence (PL) band has been observed [10, 11], although another band near 1.83 eV has been reported also [12]. In this paper, Ge nanocrystals have been fabricated and an UV luminescence peaking at 3.17 eV (391 nm) was observed with a cathodoluminescence spectroscopy. The Ge nanocrystals were formed by selective oxidation of hydrogenated amorphous SiGe/Si (a-SiGe:H/a-Si:H) multilayer prepared by a conventional plasma-enhanced chemical vapor deposition (PECVD) system and this may offer an opportunity for integration on silicon substrates. Accordingly, we presented a metal-semiconductor-metal (MSM) UV detector on Si substrate by using fabricated Ge nanocrystals embedded in SiO_2 matrix as the active medium. The detectors with MSM structure could be used to improve the feasibility of fabricating optoelectronic integrated circuits (OEICs) on a wafer because of its simple and compatible fabrication processes.

2 EXPERIMENTS

It is well-known that due to the large difference between the formation energies of Si-O (-204 kcal/mol) and Ge-O (-119 kcal/mol) [13], the Si was preferentially oxidized to form SiO_2 while Ge was rejected from the oxide and piles up along the oxide/substrate interface during the SiGe alloy oxidation process. In this study, the Ge nanocrystals had been fabricated by thermal oxidation of as-deposited a-$Si_{0.91}Ge_{0.09}$:H/a-Si:H multilayer and Figure 1 illustrates the processes of Ge nanocrystals fabrication. First, the n-type (100) Si wafer was cleaned with the standard RCA recipes, followed by a thermal dry oxidation process to grow a 20 nm oxide with a high-temperature furnace. Right after the oxide growth, the 6 periods of the a-$Si_{0.91}Ge_{09}$:H/a-Si:H multilayer were prepared with a PECVD (ULVAC CPD-1108D) system at a substrate temperature of 210 ℃ and the thicknesses of a-Si:H and a-$Si_{0.91}Ge_{09}$:H layers were designed to be 1 nm and 2 nm, respectively. Subsequently, the Si wafer with as-deposited a-$Si_{0.91}Ge_{09}$:H/a-Si:H multilayer was oxidized with a high-temperature furnace at various temperatures and durations in dry O_2 ambient and then the Ge atoms would be segregated from the growing oxide. The luminescent properties of the formed Ge nanocrystals embedded in SiO_2 matrix were characterized by using a cathodoluminescence (CL) spectroscopy. Furthermore, the MSM UV detectors with Ge nanocrystals as active medium embedded in SiO_2 matrix were fabricated with the lift-off technique to form the Cr-Au finger-electrodes and pads.

3 RESULTS AND DISCUSSION

Figure 2 illustrates the CL spectra of the 6-periods a-Si$_{0.91}$Ge$_{0.09}$:H/a-Si:H multilayer thermally oxidized at 900 ℃ for various durations of 90, 120 and 150 min., respectively. The CL spectra were measured at room temperature in the wavelength range of 200-800 nm with a monochromator resolution of 0.3 nm. The CL spectra have the same line shape and present an UV band peaking approximately at 391 nm (3.17 eV) with a full-width at half-maximum (FWHM) of 60 nm (0.048 eV). This narrow bandwidth makes it very sensitive to specific band around the wavelength of 391 nm. In order to confirm the origin of CL peaks illustrated in Figure 2, the CL spectra of Si wafer with the top as-deposited a-Si$_{0.91}$Ge$_{09}$:H/a-Si:H multilayer or with the thermally grown oxide only were measured at the same conditions, and no photoemission was observed. So, we could infer that the prominent CL signals are strongly correlated to the presence of Ge nanocrystals. Since the first observation of photoluminescence from Ge nanocrystals embedded in SiO$_2$ matrix [14], relevant light emissions due to Ge nanocrystals have been extensively studied. If the interface traps between Ge nanocrystals and SiO$_2$ are possible sources of luminescence, the CL intensity would increase with increasing Ge nanocrystass total surface area. In our work, the total surface area per volume of Ge nanocrystals formed by 120 min. oxidation (density of 1.91 x 10^{11} cm^{-2}) is 1.3 times that of Ge nanocrystals formed by 150 min. oxidation (density of 1.5 x 10^{11} cm^{-2}); therefore, the interface traps of Ge nanocrystals/SiO$_2$ are possible origin of the increased CL intensity. In addition, since the as-deposited a-Si$_{0.91}$Ge$_{09}$:H/a-Si:H multilayer is oxidized at high temperature of 900 ℃ with durations of 90, 120, 150 min., the SiO, GeO or Si-Ge-O compounds may formed also. Generally, we could assume that the UV luminescence is generated by recombination in defects located at the interface between the Ge nanocrystals and/or SiO, GeO, Si-Ge-O dielectric medium [10, 11].

Figure 3 illustrates the SEM micro-graph of the 6 periods of a-Si$_{0.91}$Ge$_{0.09}$:H/a-Si:H multilayer thermally oxidized at 900 ℃ for 120 min.. It could be clearly observed that the formed Ge nanocrystals had been well separated to each other. The sizes of formed Ge nanocrystals were ranging from 20 to 40 nm and the density of formed Ge nanocrystals was about 1.91 x 10^{11} cm^{-2}.

Figure 4 illustrates the SEM micro-graph of a fabricated MSM UV detector with finger-electrodes and pads. The active area, finger-electrode spacing and width are about 115 x 80 μm^2, 6.5 μm and 2 μm, respectively.

Figure 5 illustrates the photo-currents and dark-currents of the fabricated MSM UV detectors measured at room temperature with various finger and space widths. The responsivity, photo-current, and dark-current of the fabricated device with 2 μm finger width and 6 μm finger spacing were 0.0086 (A/W), 125 μA, and 4.78 nA, respectively, and the device photo-to-dark current ratio (I_p/I_d) could reach 2.6 x 10^4, under a 25 V bias voltage and 0.404 μm incident laser light power of 15 mW. The device photo-current increased and dark-current decreased, which lead to an increased I_p/I_d ratio, as finger spacing increased. The fewer the finger-electrodes indicated the larger the active area resulted in the higher device photo-current. The more the finger-electrodes indicated the narrower the finger spacing for the same active area led to a higher device internal electric-field and hence induce the higher device dark-current.

In addition, the transient responses of the fabricated MSM UV detectors were measured also. The 3-dB bandwidths of the fabricated devices being biased at 20 V with the same finger width of 2 μm and different finger spacing of 3, 4, 5 and 6 μm were estimated to be 262.5, 248.23, 234.9 and 221.52 Hz, respectively, as measured with the periodic light pulses from 0.404 μm laser light chopped with a chopper. The fabricated device with 3 μm finger spacing had the lowest transient fall-time due to the larger electric-field in device would result in a higher drift velocity of carriers. Since the formed Ge nanocrystals were embedded in a SiO$_2$ matrix, the carrier transport might be dominated by the field-enhanced tunneling. Therefore, the device 3-dB bandwidth was low because of the large native energy barrier of SiO$_2$.

4 CONCLUSION

The MSM UV detectors with Ge nanocrystals as active medium embedded in SiO$_2$ matrix had been fabricated on Si substrate. The direct-current and transient characteristics of the fabricated MSM UV detectors have been investigated, also. The accomplishment of MSM UV detector based-on group Ⅳ nanocrystals leads to employ the indirect-gap semiconductors as new materials for future optoelectronic applications.

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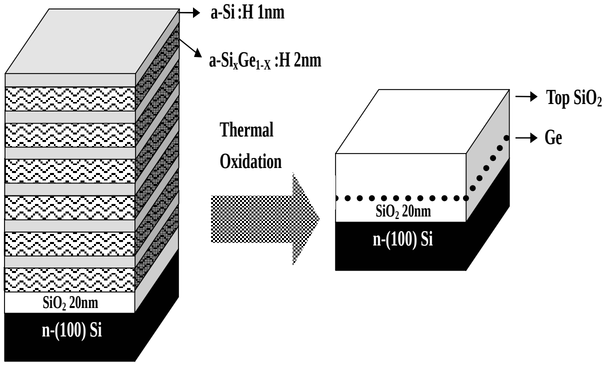

Figure 1: The processes of Ge nanocrystals fabrication.

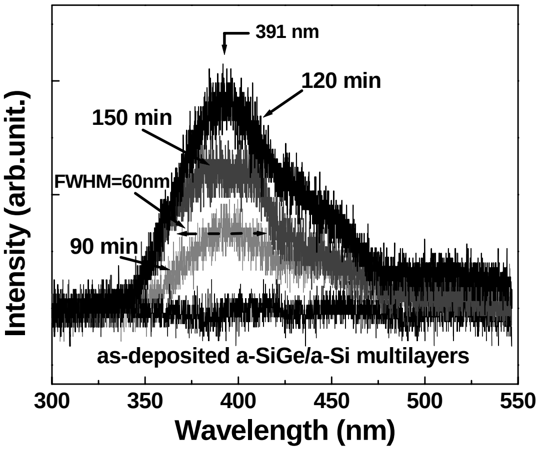

Figure 2: Room temperature CL spectrum of 6 periods of a-$Si_{0.91}Ge_{0.09}$:H/a-Si multilayers thermally oxidized at 900 ℃ for various durations.

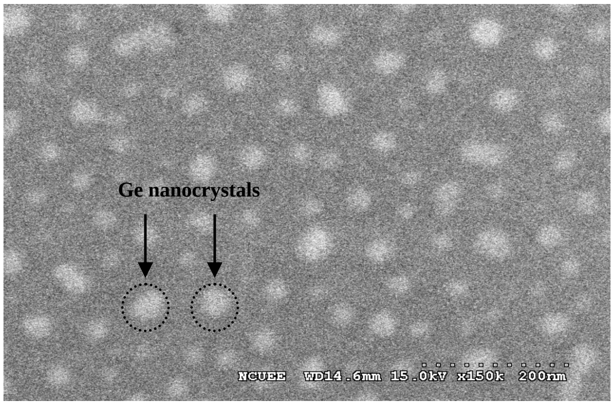

Figure 3: SEM micro-graph of the Ge nanocrystals obtained from 6-periods of a-$Si_{0.91}Ge_{0.09}$:H/a-Si:H multilayer thermally oxidized at 900 ℃ for 120 min..

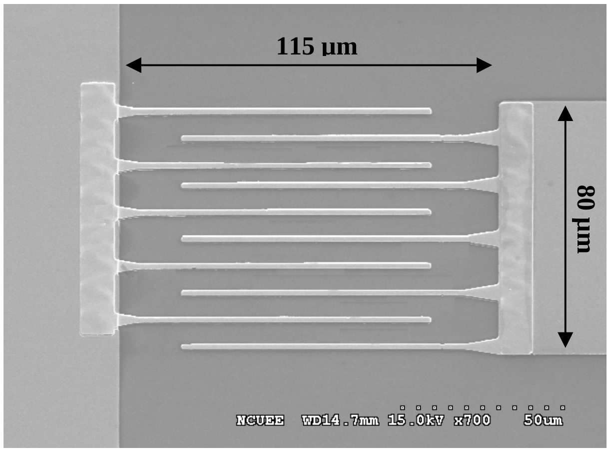

Figure 4: SEM micro-graph of the fabricated MSM UV detector with finger-electrodes and pads.

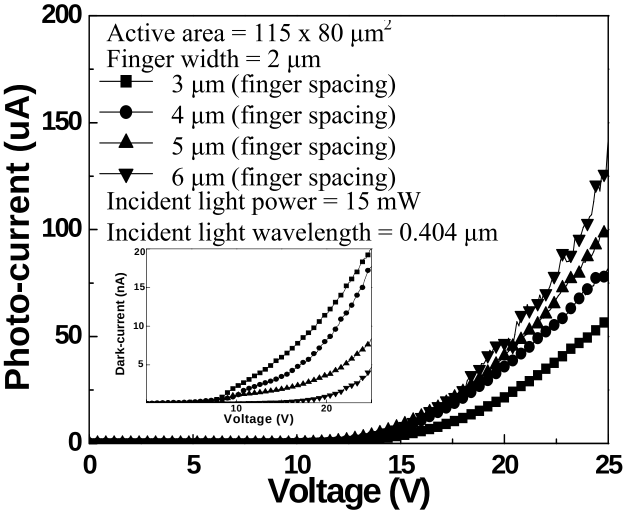

Figure 5: Photo- and dark-currents of the fabricated MSM UV detectors.