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View online: http://dx.doi.org/10.1063/1.3156806
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Near-infrared silicon quantum dots metal-oxide-semiconductor field-effect transistor photodetector

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(Received 13 February 2009; accepted 1 June 2009; published online 17 June 2009)

A fully silicon-based metal-oxide-semiconductor field-effect transistor is demonstrated for the detection of near-infrared light. Si nanocrystals (nc-Si) are synthesized in the nanopore channels of mesoporous silica (MS) inserted between two oxide layers to form a complete gate structure of polycrystalline Si/ SiO2/ nc-Si-in-MS/ SiO2 with a polycrystalline Si electrode. Illuminating the gate with near-infrared light, a photoresponsivity as high as 2.8 A/W at 1.55 µm can be achieved. The improved photoresponsivity is attributed to optical transitions via interface states and a current amplification mechanism of the device. © 2009 American Institute of Physics.

[DOI: 10.1063/1.3156806]

Silicon (Si) optoelectronics is one of the highly desired developments in photonics owing to its full compatibility with the silicon microelectronics industry. Unfortunately, bulk Si crystal is unsuited for applications as light source and detector in the telecommunication wavelength region (1.3 µm < λ < 1.6 µm) because Si crystal does not absorb long-wavelength photons efficiently. Recently, enabling by nanotechnology the concept of functionality by design has attracted significant interest of researchers. Based on the concept, “architectural photonics” has been developed to yield improved functionality by tailoring the device geometry or the structure of material used.

Optoelectronic properties of Si nanocrystals (nc-Si) are quite different from their bulk counterpart. Although silicon belongs to an indirect bandgap semiconductor, nc-Si embedded in SiO2 exhibit visible photoluminescence with high efficiency.1 In our previous study, we found that nc-Si synthesized in the nanopore channels of mesoporous silica (nc-Si-MS) can yield an improved optoelectronic response over the visible spectrum region.2 High-speed Si optical modulator with a metal-oxide-semiconductor (MOS) structure3 had been proposed as a core component of Si photonics. Along this thinking, Si-based near-infrared (NIR) detector is also highly desired. Si-based NIRQ detection had been demonstrated with a porous-Si Schottky barrier photodetector (PD). However, due to its non-thin-film-based technology the porous-Si Schottky barrier device cannot integrate with other devices to form an optoelectronic system.

Recently, a three-terminal MOS field-effect transistor (MOSFET) PD with Ge gate4 as the NIR light absorption layer had been reported. The photoexcited carriers in the Ge gate, generated by 1.55 µm NIR light absorption, form a net gate current due to band bending under gate bias. The gate current changes the gate structure and results in an accumulation of electrons and holes at either side of the gate insulator. A carrier density increase in the channel layer then raises the gate current at the drain terminal.

In this letter, we report an nc-Si/MS based three-terminal MOSFET, which exhibits an improved NIR optoelectronic response. The operational principle of our nc-Si/MS based three-terminal MOSFET PD is different from the scenario depicting above.3 We show that the nc-Si/MS can be employed to surpass the limit of the fundamental bandgap of bulk silicon crystal. The formation of nc-Si in mesoporous silica modifies the surface bonding structure of the pore channels,6 inducing enhanced optoelectronic response in the material.2

We first characterized the optoelectronic response of a nc-Si/MS layer by fabricating a two-terminal MOS on a p-type Si substrate with the structure of indium tin oxide (ITO) electrode/ (nc-Si/MS)/ p-Si. The resulting photoresponsivity is presented in Fig. 1 with open symbols. For comparison, the photoresponsivity of a pn diode (namely, ITO/n-Si/p-Si) is also included (the dashed line). The photoresponsivity of this reference device reversely biased at 5 V increases with wavelength from 300 to 900 nm. The spectral response of the device is restricted to below 1.1 µm from the limit of silicon fundamental bandgap.

The measured photoresponsivity of the ITO/(nc-Si/MS)/ p-Si PD at the same bias voltage lies in the range of 0.4–1.0 A/W from 320 to 900 nm, significantly higher than those of the reference Si PD. In the visible spectral region, our ITO/(nc-Si/MS)/p-Si MOS PD exhibits three resonances at 420, 560, and 770 nm with peak values of 0.4, 0.7, and 0.9 A/W, respectively. The improvement was attributed to a transistor-like gain mechanism. At a reverse bias, the primary photoexcited carriers generated in the Si quantum dots (QDs) of the nc-Si/MS layer can be amplified with electron injection process from the inversion layer through the MS dielectric to the ITO electrode. An optoelectronic conversion efficiency as high as 800% had been achieved.

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achieved. The appearance of resonances in the visible spectral region shown in Fig. 1 suggests that the optical response could be resonantly enhanced with the electronic structure of nc-Si/MS. The photoresponse peaks at 420 and 560 nm correspond to a resonant energy of 3.0 and 2.2 eV, respectively. The energy difference between the two resonances is 0.8 eV, suggesting an intraband transition at 1.55 μm to be allowed. The gap existing from 1.2 to 1.3 μm in the photoresponse spectrum of our ITO/(nc-Si/MS)/p-Si MOS PD indicates that the observed NIR optoelectronic response longer than 1.3 μm could not be due to transitions via bandtail states. The measured photoresponsivity of our ITO/(nc-Si/MS)/p-Si MOS PD from 1.3 to 1.9 μm is also higher than that of other nc-Si MOS device by eight orders of magnitude.

The schematic energy-level diagram shown in Fig. 2(a) was drawn to facilitate the illustration of the optical transitions involving in nc-Si/MS. The absorption process of incoming visible photons can take place directly inside the embedded Si QDs or via interface states between QDs and mesoporous silica matrix; while for the NIR photons, transitions via nc-Si/MS interface states dominate.

We fabricated a fully Si-based NIR MOSFET PD (Ref. 5) with a thin-film transistor process. The device comprises a gate structure of polycrystalline Si/SiO2/nc-Si-in-MS/SiO2, as depicted in Figs. 2(b) and 2(c), possessing a 6 μm long channel with a width of 25 μm made from an epitaxial Si layer on a quartz substrate. The gate dielectric structure consists of a 55 nm thick nc-Si/MS film sandwiched between two 20 nm thick oxide buffer layers. The source and drain regions of the MOSFET were doped with PH3 (5.0 × 1013 cm−2 at 25 keV) and then activated by a 532 nm cw laser with an averaged power of 2.2–2.8 W.

The MOSFET detector was characterized by measuring the curves of drain current (Id)–gate voltage (Vg) and drain current (Id)–drain voltage (Vd). The Id–Vg curves of the MOSFET device with the gate being kept in the dark or illuminated with NIR light at 1310 and 1550 nm are presented in Fig. 3(a). Hole trapping in the illuminated gate produces a built-in potential that adds to an external bias (Vg) to generate a negative shift (ΔVth) of the threshold voltage (Vth). Therefore, the device with illuminated gate generates a higher drain current. The threshold voltage shift depends on the density of trapped holes [see Fig. 3(b)]. As the device is irradiated with 1.55 μm light, ΔVth becomes larger than that with 1.3 μm light, implying that 1.55 μm photons can more efficiently generate photoexcited carriers at the interface states of nc-Si/MS. In the off-state with negative Vg, the photocurrent generated by NIR light is very low due to a very low leakage experienced by the drain current at the reversely biased drain-to-channel junction.

The Id–Vd characteristics of the MOSFET PD operated at various gate bias voltages with the unexposed gate structure or illuminated with it at 1310 and 1550 nm light, respectively, at an irradiance of 4 nW/μm2 are presented in Fig. 4(a). The corresponding photoresponsivity is shown in Fig. 4(b). The wavelength (1.3 μm < λ < 1.6 μm) dependence of the photoresponsivity is plotted in Fig. 1 with a solid curve, revealing the photoresponse of the MOSFET PD at 1550 nm to be 2.8 A/W at Vg = 1.6 V and Vd = 3 V. The high photoresponsivity can be attributed to a current gain from the transistor mechanism.

An energy-level model was proposed to illustrate the experimental observations reported above. Without illumination, the device behaves like a normal MOSFET. When the gate voltage (+Vg) is higher than the threshold voltage, a significant number of electrons can accumulate at the interface between the gate structure and the epitaxial Si channel to
form an n-type inversion layer. As a result, the gate voltage induces a drain current. When the energy of an incident photon matches a difference between an occupied electronic state to an empty excited state, a strong absorption occurs. The lowest energy of photons can be absorbed by a bonding structure located at an interface is the energy gap between the highest occupied molecular orbital and the lowest unoccupied orbital. The most likely interfacial states are the bonding orbitals of Si-O. Under an applied electric field, the photoexcited electrons can tunnel to the interface of the upper blocking oxide layer and the nc-Si/MS layer. The holes, however, are trapped at the interface states. The immobilized positive charges with accumulated electrons at the oxide/nc-Si/MS interface form a net polarization in the nc-Si/MS layer as illustrated in Fig. 2(a). This polarization enhances the influence of the gate voltage (+V_g) and increases the channel conductance, which causes more electrons to flow from the source to the positively biased drain terminal.

In the nc-Si/MS MOSFET PD, a very small increase in the gate current (∼22−79 pA at V_g=0−3 V and V_d=3 V, data not shown) under illumination ensures the MOSFET to operate in the “voltage-controlled-current” mode. The optical absorption by silicon nanocrystals is extremely fast in the order of picoseconds. Therefore, the gate response time τ is mainly limited by the transport time of the photoexcited carriers. For a gate structure with 55 nm thick (d) nc-Si/MS, we estimated the response time to be about 1 ns by using \( \tau=d^2/(V\mu) \), where V is the applied bias and \( \mu \) is the effective mobility of nc-Si/MS. The effective mobility of our nc-Si/MS was determined to be \( 10^{-2} \text{ cm}^2/\text{V s} \) from the observed photoresponse time (10 ns) on a 220 nm thick nc-Si/MS MOS PD. Note that this value is about one order of magnitude higher than the reported result with a thin film of Si nanoparticles. For the nc-Si/MS three-terminal MOSFET PD, a device response time of 2 ns was achieved, which is mainly limited by the carrier transport time of the micrometers-long epi-Si channel used.

In summary, we had developed an nc-Si MOSFET PD to surpass the limitation of the fundamental bandgap of bulk silicon crystal. The absorption in the NIR region of 1.3 μm < λ < 1.6 μm can occur via transitions in nc-Si/MS interface states. The photocarriers generated by NIR photons in the nc-Si/MS gate layer enhance the influence of gate bias and result in an increase in the electron density in the inversion layer of the channel. The phototransistor mechanism of our device further amplifies the photoresponsivity at 1.55 μm to 2.8 A/W.

The authors would like to thank the National Science Council of the Republic of China, Taiwan for partially supporting this research.