Novel MIS Ge–Si Quantum-Dot Infrared Photodetectors

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***Abstract*—The metal–insulator–semiconductor (MIS) Ge–Si quantum-dot infrared photodetectors (QDIPs) are successfully demonstrated. Using oxynitride as gate dielectric instead of oxide, the operating temperature reaches 140 and 200 K for 3–10 and 2–3 μm detection, respectively. From the photoluminescence spectrum, the quantum-dot structures are responsible for the 2–3 μm response with high operation temperature, and the wetting layer structures may be responsible for the 3–10 μm response. This novel MIS Ge/Si QDIP can increase the functionality of Si chip such as noncontact temperature sensing and is compatible with ultra-large scale integration technology.**

***Index Terms*—Ge, metal–insulator–semiconductor (MIS), oxynitride, quantum-dot infrared photodetectors (QDIPs), quantum-dot.**

I. Introduction

Due to the low dark current, high operation temperature, and normal incident detection, the quantum-dot infrared photodetector (QDIP) is very attractive in military, medical, astronomical, and other applications. The most common material systems used for the QDIPs are III-V-based systems. The QDIP with the self-assembled InGaAs quantum-dots has been demonstrated with 3.25 mA/W responsivity at 60 K, with the wavelength of 9.2 μm [1]. Tang *et al.* also demonstrated the ten stack InAs–GaAs QDIP at 2.5–7 μm with 2.4×10^8 cm-Hz$^{1/2}$/W detectivity at 250 K [2]. The III-V-based QDIP has reached an operation temperature of 260 K using the InGaAs–GaAs quantum-dots due to the low dark current and long carrier lifetime in the quantum-dots [3].

Due to the compatibility with Si ultra-large scale integration (ULSI) process and the tremendous capability of digital signal process on Si chip, the Si–SiGe heterojunction photodetectors are desired to have the infrared detection wavelengths beyond 1.1 μm. The metal–insulator–semiconductor (MIS) Ge quantum-dot photodetector have been reported with 1.3 and 1.5 μm responses [4]. In this letter, the MIS Ge–Si QDIP is demonstrated using the hole subband transitions of the quantum-dot and wetting layers. By using the tunneling junction in the MIS structure as a current blocking barrier, the dark current is reduced as compared to the metal-semiconductor–metal (MSM) devices [2], [3].

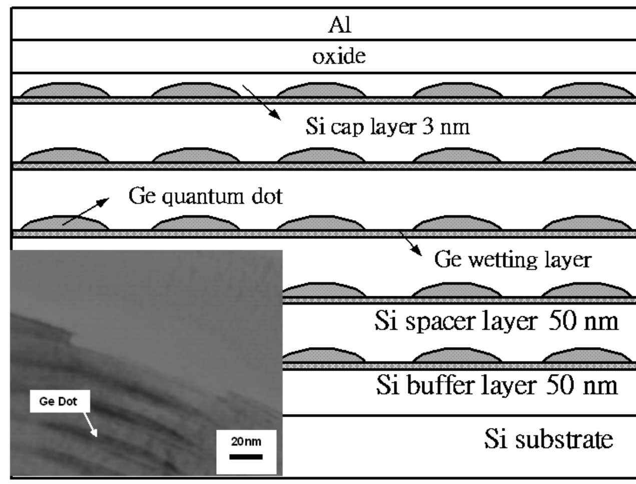

Fig. 1. Structure of the MIS Ge–Si QDIP. The five-layer Ge quantum-dots were prepared by ultrahigh-vacuum chemical vapor deposition, and the inset shows the TEM micrograph of the self-assembled Ge dots.

II. Device Fabrication

The schematic structure of the MIS Ge–Si QDIP is illustrated in Fig. 1 and the transmission electron microscopy (TEM) image of the Ge quantum-dot is shown in the inset. After an Si buffer layer of 50 nm, five periods of self-assembled Ge–Si quantum-dots were grown on a p-type Si substrate at 600 °C under the Stranski–Krastanov (SK) growth mode [5]. Silane (SiH_4) and germane (GeH_4) were used as the Si and Ge precursor, respectively. To separate the Ge layers, a 50-nm Si spacer layer was used and a 3-nm Si cap was deposited as a top layer for the subsequent dielectric growth. The base width and height of the Ge dots are $\sim$100 and $\sim$7 nm, respectively. The Ge dot density is $\sim 10^{10}$ cm^{-2}, measured on the sample with the same growth condition without the Si cap. All layers were unintentionally doped with an estimated hole concentration $\sim 1 \times 10^{16}$ cm^{-3}.

The MIS QDIPs had Al gate electrodes with various circular areas defined by photolithography. To avoid strain relaxation and Ge segregation, low-temperature liquid phase deposition (LPD) process was used to deposit the gate oxide with the advantages of low cost, selective growth, and high throughput [6].

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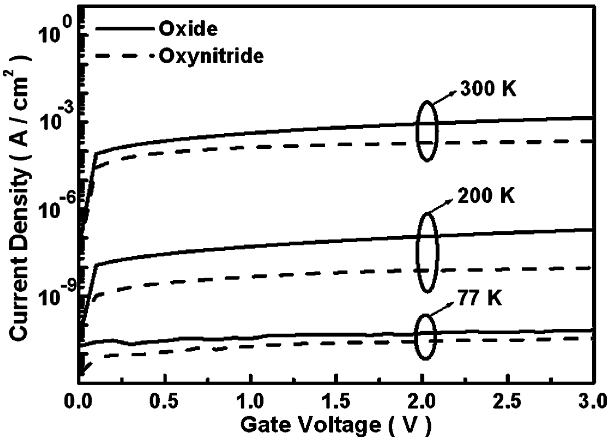

Fig. 2. Dark current of MIS Ge/Si QDIPs with LPD oxide and oxynitride at different temperature. The device with oxynitride has lower dark current density.

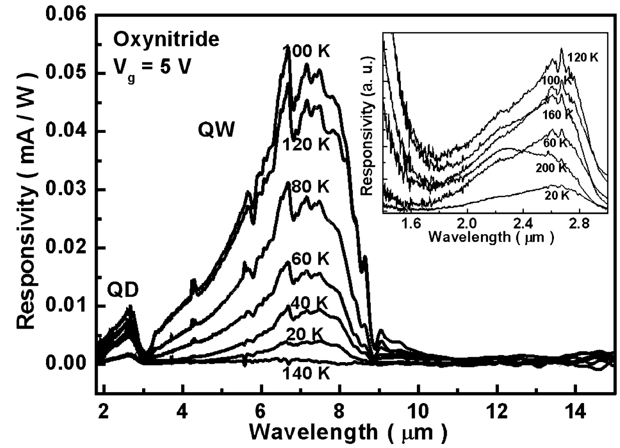

Fig. 3. Spectral responsivity of the device with oxynitride at different temperature. The operating temperature is 140 K for 3–10 μm detection. The inset shows the 2–3 μm response and the operating temperature reaches 200 K.

Details can be found in the [6]. To further reduce the dark current, NH_4 OH was added into the saturated solution during LPD process to form the SiON film [7].

III. Results and Discussion

Fig. 2 shows the current–voltage (*I–V*) characteristics at different temperature for the devices with oxide or oxynitride as gate dielectrics. The thicknesses of the LPD oxide and oxynitride were ~1.5 nm. The dark current of MIS tunneling diode is dominated by thermal generation of electron-hole pairs through the defects in the depletion region and at the Si–SiO_2 interface [8]. The LPD oxynitride has a low interface state density, and thus, has a low dark current as compared to LPD oxide. For an n-channel MIS (NMIS) Ge QDIP under inversion bias, the thermally generated electrons tunnel through the insulator layer, and the holes thermally generated in the deep depletion region as well as the holes tunneling from the gate electrode are swept toward the Si substrate. The Ge quantum-dots are placed in the depletion region at inversion bias to have sufficient electrical field to drift the photo-excited holes.

The spectral responsivity of the NMIS Ge/Si QDIP with oxynitride is illustrated in Fig. 3. The infrared is normal incident to the device without any polarization. For p-type quantum wells, the optical selection rules do allow both normal and parallel incident absorption. The normal incident absorption of p-type Si–SiGe quantum wells are also reported in the previous studies [9], [10]. The spectral responsivity is calibrated with a blackbody radiation source [2]. The spectral dependence of the responsivity is measured by Fourier transform infrared (FTIR) spectrometer (Perkin–Elmer Spectrum 2000). Note that the measured spectrum is the multiplication of the light source spectrum, and the spectral response of the detector. The device spectral response is obtained after the correction of light source spectral dependence. The spectrum can be divided into two absorption regions (2–3, and 3–10 μm). For 3–10 μm detection, the peak wavelength is located at 6.8 μm and the maximum operating temperature is about 140 K. For 2–3 μm detection, the peak wavelength is located at 2.7 μm and the operating temperature is up to 200 K (Fig. 3). At low temperature, the responsivity increases with the increasing temperature due to the increasing thermal energy of confined holes in the quantum-dots and quantum wells. With higher thermal energy, more holes can relaxed to the bottom electrode without being trapped by quantum-dots after photon excitation. After ~100 k, the second bound state is more populated with holes, less holes are in the ground state, the bound-to-bound transition also becomes difficult. Therefore, the responsivity drops as the temperature further increases. Note that the strong spectral response for wavelengths smaller than 1.7 μm is due to the interband transition of the Si–Ge quantum-dots.

Since the operating temperature is higher for 2–3 μm detection, this short wavelength response probably comes from the quantum-dot structure due to the better quantum confinement, while the 3–10 μm response may be dominated by the wetting layer structure. By assuming the Ge dot is a simple box of infinite barrier, the allowed energies in the dot can be evaluated as [11]

$$E_{n,k,l} = \frac{\pi^2\hbar^2}{2m^*}\left(\frac{n^2}{L_x^2} + \frac{k^2}{L_y^2} + \frac{l^2}{L_z^2}\right) \qquad n,k,l = 1,2,3\ldots \quad (1)$$

where m^* is the Ge heavy hole effective mass equal to 0.3 m_0, L_x and L_y are dot base widths, and L_z is the dot height. L_z is ~7 nm in our sample, while L_z is 4–4.5 nm in [11]. The ground state energy of the heavy hole is ~100 meV. Fig. 4 shows the 20 K photoluminescence (PL) spectrum of the multilayer Ge quantum-dots structure. The Si bandgap at 20 K is about 1.17 eV. The PL spectrum indicates that the short wavelength response comes from the quantum-dot structure for the bound-to-continuum transition (~0.4 eV) [12]. With the ground state energy of ~100 m eV, the valence band offset between Si and Ge dots is ~0.5 eV. Note that the bandedge of the bound state is estimated as the cutoff energy at the low-energy side of the PL line in Fig. 4.

The device detectivity at 100 K reaches 10^{10} and 10^9 cm-Hz$^{1/2}$/W for 6.8 μm and 2.7 μm, respectively. The normalized detectivity D^* is defined as

$$D^* = \frac{\sqrt{A\Delta f}}{NEP} = \frac{\sqrt{A\Delta f}}{\frac{i_n}{R}} \quad (2)$$

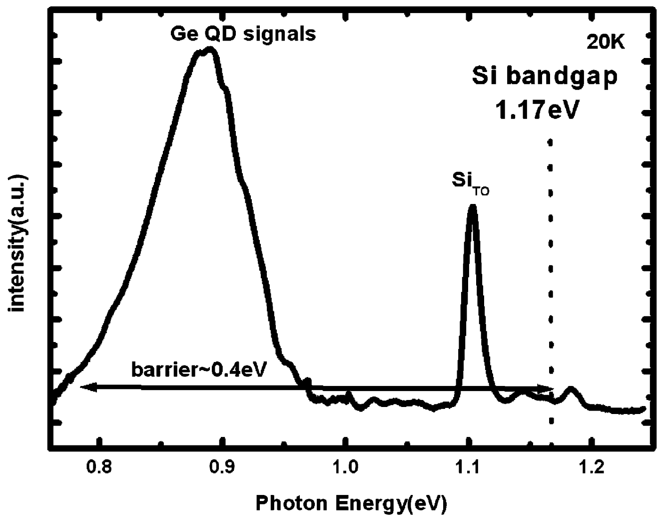

Fig. 4. The 20 K PL spectrum for a multilayer Ge–Si quantum-dot structure. Si bandgap is ~ 1.17 eV at 20 K, and the QD barrier is ~ 0.4 eV.

where A is the detector area, Δf is the equivalent bandwidth of the electronic system, and $NEP = i_n/R$ is the noise equivalent power. The i_n is current noise and R is the responsivity. The current noise is limited by the dark current and can be approximated as the shot noise $(2eI_d\Delta f)^{1/2}$, where I_d is the measured dark current. Due to the low dark current, the peak detectivity is relatively large. Due to the larger dark current of the device with LPD oxide, the operating temperature of the LPD oxide device is only 80 K for 3–10 μm detection and is 120 K for 2–3 μm detection. Note that there is no electron-hole pair generation through interface states under the infrared exposure, since the similar spectrum was observed for the Schottky contact MSM detectors [13].

IV. Conclusion

The MIS Ge–Si QDIPs using hole subband transitions are successfully demonstrated. The maximum operating temperature is 140 K for 3–10 μm and is up to 200 K for 2–3 μm detection using LPD oxynitride as gate dielectrics. Under infrared exposures, the holes confined in the quantum-dots may have bound-to-continuum and bound-to-bound transitions, responsible for the 2–3 and 3–10 μm responses, respectively. The device peak detectivity is 10^{10} and 10^9 cm-Hz$^{1/2}$/W for 6.8 μm and 2.7 μm, respectively.

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