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Ge quantum dots sandwiched between two thick Si blocking layers to block the dark current and tune the responsivity spectrum

Y.H. Peng^a, C.C. Chen^a, C.H. Kuan^{a,*}, H.H. Cheng^b

^a Department of Electrical Engineering, Graduate Institute of Electronics Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan, ROC

^b Center for Condensed Matter Sciences, National Taiwan University, Taipei 10617, Taiwan, ROC

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Abstract

A p-type Ge quantum dot infrared photodetector is investigated in this paper. The intrinsic thick Si layers are utilized to block the dark current under low bias and adjust the tunneling probability by controlling applied field to tune the responsivity spectrum. The 30 K responsivity spectrum shows broadband from 2 to 9 μm at zero bias with photovoltaic effect and extends its range to 20 μm when the applied bias is increased.

For long wavelength detection, our detector is tunable with Si blocking layer. The detectivity in this sample has maximum value toward $2.1 \times 10^{10} \text{ cm (Hz}^{0.5})/\text{W}$ under 0.2 V for the 6 μm wavelength. That for the long wavelength is $\sim 10^9 \text{ cm (Hz}^{0.5})/\text{W}$.

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1. Introduction

Quantum well infrared photodetector (QWIP) are useful in various applications such as the thermal imaging, night vision, and optical communication etc. [1–7]. Recently, the detectors realized with quantum-dot structure are particularly worthy of academic investigation because the quantum dot is a nanostructure. Due to the limitation of the polarization selection rule, QWIP will have intersubband transition only by the light polarized in the growth direction, while the quantum dot's three-dimensional confinement potential for charge carriers makes the quantum dot insensitive to the polarization direction [8–11,20]. This characteristic can make the fabrication process easier.

Although quantum dot infrared photodetectors (QDIPs) are predicted to have some important advantages over QWIPs such as lower dark current, higher internal gain and higher operation temperature [12,13], the practical detector in fact does not show the advantages. Especially some structures are needed to limit the dark current in order not to saturate the read-out circuit. In addition, Ge quantum dots (QDs) have become a hot research topic recently since this Si-based detector has the advantage of the monolithic integration with the read-out circuit [14].

In order to cut down the dark current, the detector is realized with Ge QDs that are sandwiched between two thick Si blocking layers. Since the grown Ge QDs have different sizes, the resulting excited energy states may have a broad range and the detected wavelength can then be wide. For the long wavelength detection, the energy states of the photoholes may be close to the top of the quantum dot barrier [15–21]. The two thick blocking layers can be used to adjust the electric field

* Corresponding author. Tel.: +886-2-23635251x439; fax: +886-2-23671909.

E-mail address: kuan@cc.ee.ntu.edu.tw (C.H. Kuan).

around the barrier. Under the low bias, the photoholes cannot pass the barrier. However, under high bias, the effective thickness of the barrier becomes thin due to the strong electric field. The photoholes may hence tunnel through the barrier and the apparent responsivity for the long wavelength can then be detected [22]. By manipulating the thickness of the blocking layers and quantum dot's size, we can broaden the detection range to longer wavelength and make the detector tunable in the long wavelength range.

2. Investigation of the sample structure

First of all, we grew a 7 ml Ge QDs on a Si substrate with well-grown buffer at the temperature of 600 °C, and observed the size, shape, and distribution density with

an atomic force microscope (AFM) and the experimental results are shown in Fig. 1. For the QDs as marked by the line in Fig. 1(a), the associated cross section view is shown in Fig. 1(b). From the results, we could measure the height and diameter of Ge QDs to be around 200–300 Å, and 2500 Å respectively. From the AFM picture, the calculated distribution density of Ge QDs is around $1.3 \times 10^{19} \text{ cm}^{-2}$.

Fig. 2 shows the structure of our photodetector. The growth procedure was first to deposit a 3000 Å Si buffer on p-type 1–10 Ωcm, which was doped with boron of 10^{19} cm^{-3} , to serve as the bottom contact. After that we deposited a 1000 Å undoped Si blocking layer with $2 \times 10^{16} \text{ cm}^{-3}$ background doping. Then 10 layers of multiple quantum dots (MQDs) were deposited. The growing parameter of MQDs was derived from AFM data. We deposited 7 ml Ge QDs, and added delta dope

Fig. 1. AFM picture of pre-growth surface QDs (a) and its cross section plot (b).

Fig. 2. The structure of our quantum well infrared photodetector.

in the middle of the Ge QDs. After that, 200-Å undoped Si was capped on these QDs as spacer to smoothen the surface roughness that resulted from the Ge QDs. This spacer also serves as a barrier on the energy band in order to form the quantum confinement to the hole of Ge QDs. After the MQDs came the 1000-Å undoped Si blocking layer and then the top contact layer with 3000 Å thick and $1 \times 10^{19} \text{ cm}^{-3}$ boron doped.

The whole structure was then examined by high-resolution cross-section TEM. The result is shown in Fig. 3. The width and size of the MQDs are about 200 and 1400 Å respectively. The TEM picture also shows the vertical alignment of the MQDs layer, which is resulted from strain. In addition to this, a phenomenon similar to Newton Ring is also found around the QDs in the picture, which reveals that there are strong strain field in the MQDs [23].

We also etched the heavily doped layer on the surface, and did the photoluminescence (PL) measurement at the temperature of 16 K. The result of this measurement is shown in Fig. 4(a). The PL spectra at 1.14, 1.098 and 1.036 eV are the phonon assisted transitions of TA, TO,

Fig. 3. Cross section TEM of QDIP.

(a)

(b)

Fig. 4. (a) PL spectrum at 20 K temperature; and (b) schematic energy band diagram according to PL spectrum (not to scale).

and TO_2 of Si respectively. From the discrepancy of TO and TO_2 , it is concluded that the energy of Si TO phonon is 62 meV. From the Si-TO transition energy, it is then concluded that the energy of Si band gap is 1.16 eV. In addition, the transition peaks at 0.75 and 0.766 eV are related to C-O complex and mainly come from the spectrum of substrate [24].

The range from 740 to 935 meV in Fig. 4(a) is the transition formed by Ge QDs and indicates the QD's size distribution. According to the neighboring confinement structure proposed by the Refs. [25–28], the transition of the Ge related PL is primarily from the localized state near the Si conduction band at the in-plane Si/Ge hetero interface to the ground state in the valence band of Ge dots as shown in Fig. 4(b). It originates from spatially indirect and phononless (NP) recombination between holes confined in the Ge dots and electrons confined within the tensile strained Si encompassing the coherent Ge dots. In addition, the broadness of the Ge related PL might be attributed to the size distribution of the QDs, which results in a band of the

QDs. Therefore, the levels of Ge QD ground-state band can be estimated by Ge phononless transition energy and the activation energy from the tensile strained Si. Suppose 63 meV be adopted for the activation energy [25] and the energy origin be the silicon valence band edge. The uppermost and lowermost level of the ground-state band in the Ge dots can be calculated as 162 and 357 meV respectively as shown in Fig. 4(b).

A standard process of the detector fabrication was also performed on the sample. A mesa of $300 \times 600 \mu\text{m}^2$ protruding to the middle of bottom contact layer was etched. When 1500 Å Al was deposited at the top and bottom of the mesa, the rapid thermal annealing proceeded immediately to form ohmic contacts.

3. Characterization of our detector

The I - V characteristics of the detector were measured to analyze its electric property. The dark current (solid curves) versus biases at different temperatures and background photocurrent (dashed curves) at 20 K are showed in Fig. 5. The dark current at 20 K is extremely low compared with conventional QDIP. At low bias, the dark current is lower than 10^{-11} A, and appears to be turned on at 1.2 V bias.

The associated turn-on voltage decreases with increasing temperature. From 20 to 40 K, the turn-on bias decreases from 1.2 to 0.5 V, and decreases to zero at 50 K, i.e. there is no turn-on phenomena above 50 K. Similar situations occur when negative biases are applied. On the other hand, there is no turn-on phenomenon on the background photocurrent but there is a photovoltaic effect at zero bias. It indicates that the background photocurrent does not encounter any bar-

rier [29]. When we compare it with the dark current at 20 K, it is found that the background photocurrent is 10^3 larger than the dark current under 1.2 V bias.

The dark current under low bias is attributed to the thermionic emission of holes after turning on; the current is dominated by the thermally assisted tunneling [30]. From the difference of dark and photocurrent level, we estimate the background-limited performance is toward 40 °K when we applied bias lower than 0.7 V.

From Fig. 5, it is noted that the dark-current level is reduced obviously by two thick Si blocking layers. Suppose that the maximum voltage of the read-out circuit in the thermal imaging application is 5 V and the charge capacitance with the same area as our detector is 1 nF. If the reading time is 30 ms to reach low noise, then the maximum dark current is about 0.17 μA . If the operating temperature of our detector is 50 K, then the applied bias should be less than 0.5 V in order not to saturate the capacitance. If the detector is to operate in the background limited performance, the applied bias has to be less than 0.3 V.

The responsivity versus wavelength at 30 K for positive biases is shown in Fig. 6. The responsivity broadband of our QDIP at zero bias ranges from 1.6 to 9 μm . With the increase of bias, the spectrum gradually reaches over 20 μm at 1.0 V bias. At zero bias, the spectrum shows that only photons with energy over 9 μm can trespass the barrier and then be collected by the contact layer to form photocurrent. It is the photovoltaic effect as described in previous paragraph. While the bias increases, the spectrum extends from 9 μm toward longer wavelength and the responsivity for the long wavelength hence increases. Under 1.0 V bias, it can be extended to be longer than 20 μm .

Fig. 6 indicates that there are involved with two mechanisms for the photohole to be emitted over and

Fig. 5. I - V curves for QDIP. The solid lines are dark current at 20–60 K temperatures. The dash line is photocurrent at 20 K temperature.

Fig. 6. Response spectra at 20 K temperature with various bias from 0–1 V.

tunnel through the barrier of the QDs. The key wavelength to separate these two mechanisms is about 9 μm . The photoholes excited by the photons with wavelength less than 9 μm have enough energy to be emitted over the barrier so that the photovoltaic effect appears at zero bias [29]. On the other hand, the photoholes excited by longer wavelength does not have enough energy and have to tunnel through the barrier with the help of the strong electric field so that the responsivity in Fig. 6 extends to longer wavelengths and shows the advantage of the tunable spectrum under the applied bias.

Since the band offset of Ge QDs and Si on the valence band is very large, it is expected that there would be at least two bands of energy states in the QDs [31]. From the photovoltaic effect in Fig. 6, it is concluded that the depth of the ground-state band is 138 meV, which is close to 162 meV derived from PL and shown in Fig. 4(b). The discrepancy depends on the choice of the cut-off wavelength of the photovoltaic effect. If 8 μm is chosen, the agreement between the responsivity and PL becomes obvious. From the longest wavelength of responsivity, we can determine the gap between the lowest level of the second band in QDs and the silicon barrier. Since the responsivity is cut off at 62 meV, the gap for the second-band bottom state to the Si barrier is about 100 meV. Since the value is not very large, it is possible for the associated photoholes to tunnel through under enough bias. To demonstrate the relation about the transition energies, a simplified band diagram for Ge QDs is showed in Fig. 8.

The specific detectivity for different wavelengths versus bias at 30 K is shown in Fig. 7. The detectivity in this device has maximum value toward $2.1 \times 10^{10} \text{ cm (Hz}^{0.5})/\text{W}$

Fig. 8. The simplified band diagram for QDs in QDIP.

under 0.2 V for the 6 μm wavelength. The detectivity for the long wavelength is $\sim 10^9 \text{ cm (Hz}^{0.5})/\text{W}$. From the shape of the curve, we can divide the detectivity into two portions. The detectivity for the short wavelength appears higher. With the increase of bias, the maximum value of the detectivity is at around 0.2 V. Over the maximum point, the detectivity decreases with the increase of the bias due to the large dark current. The detectivity for the long wavelength increases as the bias increases because of the increment of the tunneling photohole current [32,33]. The division of the two portions originates obviously from the two mechanisms of the photoholes as discussed in the previous three paragraphs.

Fig. 7. Different wavelength detectivity under 0–1.0 V bias. There are two behaviors for these curves; one has its maximum under 0.2 V and decrease while bias increasing. The other is increasing while bias increasing. The two types of these curves are divided by 10 μm curves.

4. Conclusion

We have successfully demonstrated a QDIP in our preliminary work on Ge QDs devices. In IR responsivity property, our QDIPs have a very broad and tunable spectrum of 1.6–20 μm under applied biases. This is very useful to apply these QDIPs in thermal image detection. For detectivity, the maximum single wavelength detectivity of our devices is about $2.1 \times 10^{10} \text{ cm (Hz}^{0.5})/\text{W}$ under 0.2 V for 6 μm wavelength at 30 K. The I – V characteristics shows that the dark current is reduced by the thick Si blocking layers so that the detector can be applied in the thermal image detection. The responsivity at zero bias is around 1.6–9 μm . We can increase the responsivity from 9 to 20 μm with the external bias. The tunability of the responsivity spectrum under the applied bias results from the utility of the two mechanisms of the photoholes to be emitted over or tunnel through the silicon barrier.

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