C–V and AS study of self-assembled Ge islands in Si p-n junction

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Abstract: - The electrical properties of self-assembled Ge quantum dots (QDs) and Ge quantum wells (QWs) embedded in Si p-i-n diodes were studied using capacitance-voltage measurements and admittance spectroscopy. The investigated samples were grown on Si(001) substrates by an ultra high vacuum chemical vapour deposition (UHV-CVD) system. A linear increase of the thermal activation energy observed in voltage-dependent admittance spectroscopy for the sample with quantum dots shows that the ensemble of Ge islands has a low, continuous, averaged density of states.

Key-Words: - Quantum dot, quantum well, admittance spectroscopy, lateral photodetector.

1 Introduction

Modern semiconductor technologies nowadays combine more than 10 million transistors on a single chip, forming an intergrated circuit that is extremely complex and sophisticated. With the progress in semiconductor technologies, it can be expected that a single element in such circuits may be scaled down to a size of a few nanometers or a few tens of nanometers in the nearest future. However, a device of such small dimension represents new phenomena, leading to very different operation mechanisms as compared to those of conventional devices. Nanostructures based on the germanium-on-silicon heterosystem attract the attention of technologists owing to significant progress in the development of new quantum-effect devices. In recent years, the potential applications of the Ge/Si-based semiconductor materials containing the nanometer-sized Ge clusters(quantum dots) embedded in the Si matrix have become apparent.

Self-assembled quantum dots can be grown with high structural quality and relatively high homogeneity by molecular-beam epitaxy (MBE) or chemical vapour deposition (CVD). The unique optical and electrical properties of such quantum dots stimulated intense research activities, and some novel optoelectronic devices such as quantum-dot lasers[1], optical memory structure[2-4], and lateral intersubband detectors[5,6] have been demonstrated.

In this work, we present the results of an admittance spectroscopy study on medium-size Ge islands embedded in Si p-i-n diodes. The C-V measurements are also presented. We show that for one sample the activation energy obtained from the admittance measurements increases linearly with the applied bias and conclude that these islands on the average have a low, continuous, density of states. Also we demonstrate that for other sample the activation energies remain constant with the applied bias and connect that with existence of the high carrier concentration in some regions of the structure.

2 Sample growth and device structure

The investigated samples were grown on Si(001) substrates by a commercial available ultra-high vacuum chemical vapor deposition (UHV-CVD) system. Pure SiH4 and 5 % He-diluted GeH4 were used as the precursor gas. After depositing an 300-nm Si buffer layer on the substrate, five- and ten-fold stacks of Ge/Si bilayers were then deposited at 600 ℃. Finally, the layer structures were completed by depositing 150-nm Si cap layer(Fig.1). After growth, the samples were processed into mesas with different area for C-V measurements. In this study, four samples with different B_2H_6 pretreatment before QD

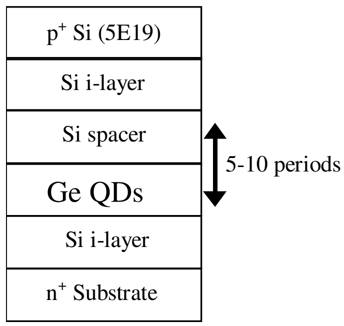

Fig.1. Schematic picture of the p-i-n diode layer geometry used.

growth and quantity of Ge QD layers were grown.

3 C-V and Admittance spectroscopy

In order to study the level scheme in the valence band of our samples, admittance measurements are performed. In these measurements, the ac conductance and capacitance of the sample are measured as a function of temperature for various fixed external bias voltages.

In principle, the quantum dots can be generally considered as carrier traps, so that the analysis of quantum dot admittance spectroscopy will be similar to that of defects in bulk semiconductors. For a dot layer embedded in the p-type region of a space-charge structure, approximate equivalent circuit for junction admittance can be considered as a quantum dot charging capacitance C_d in series with a charging resistance R_d , and then in parallel with a depletion capacitance C_0 representing the free-electron contribution(Fig. 2).

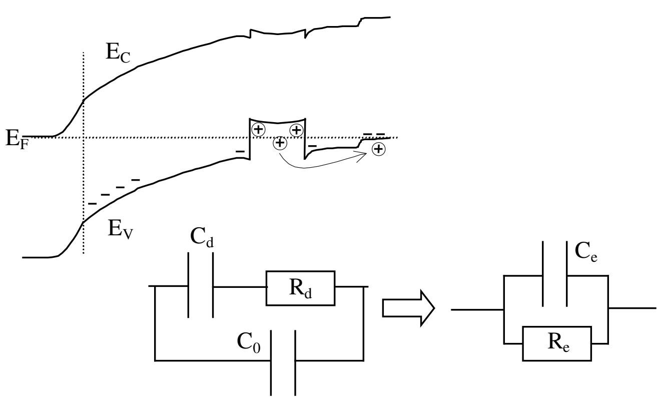

Fig.2. Schematic band structure and equivalent cuircuit model for describing the dot layer embedded in the p-i-n diode.

When a test signal of angular frequency *w* (*w*=2π*f*) is applied, under the parallel measurement mode, the equivalent conductance G_p and capacitance C_p seen by the capacitance meter are given by

$$C_e(w,T) = C_0 + \frac{C_d}{1+w^2\tau(T)^2} \quad (1)$$

$$G_e(w,T) = C_d \frac{w^2\tau(T)}{1+w^2\tau(T)^2} \quad (2)$$

where $\tau(T) = R_d C_d = \frac{1}{\sigma \cdot b \cdot T^2} \exp\left(\frac{E-E_V}{kT}\right)$.

As shown in Fig.2, when the Fermi level intersects with the dot level, the applied ac voltage will cause an alternate filling and emptying of the dots.

Looking at AS data for the sample without Boron pretreatment(Fig.3) we can see that capacitance steps always occur at the same temperatures under different reverse bias voltages. The constant step position indicates a nearly constant Fermi energy and an effective screening of the electric field by the accumulated charge.

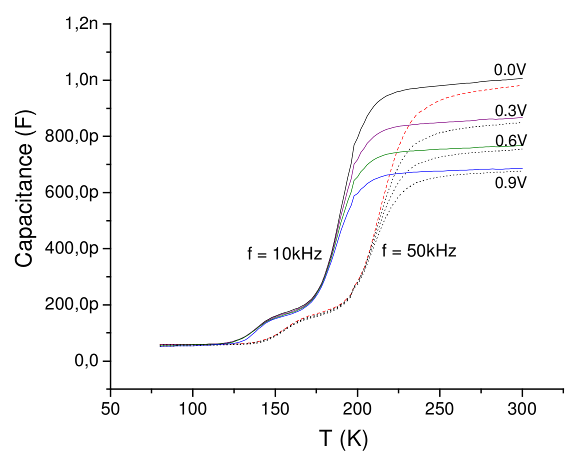

Fig.3. Admittance spectra of the sample without Boron pretreatment for the measuring frequencies 10kHz and 50kHz at different bias conditions.

It is known from literature[7] that according to a self-consistent band-structure calculation, the 6-nm-thick $Si_{0.7}Ge_{0.3}$ quantum well has two confined states, a heavy-hole state with a localization energy of 197meV and a light-hole state with 128meV.

From our AS data for the sample without Boron pretreatment (Fig.3) we have two levels with activation energies about 132meV and 202meV. These activation energies are about constants in some reverse bias region. So it is most likely that our

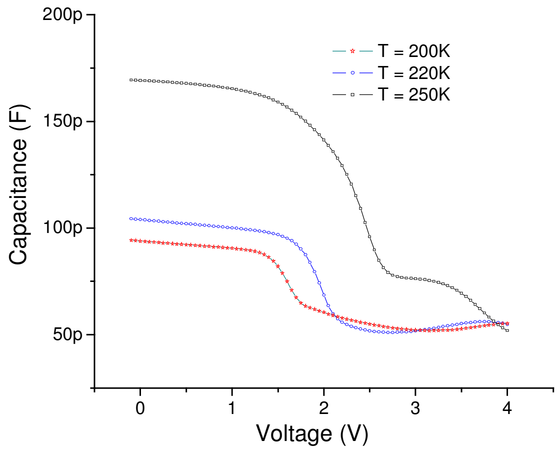

Fig.4. C-V curves at different temperatures for the sample without Boron pretreatment at a measuring frequency 1MHz.

sample has quantum wells with the 202 meV heavy-hole state and the light-hole state with 132meV.

The results of the C-V measurements taken on the sample without Boron pretreatment are shown in Fig.4. On the C-V curves we can see a vast plateau that is evidence of the big carrier concentration in the investigated region. In one's turn this is in compliance with AS data. Also one can see that for higher reverse bias voltages the increasing leakage current of the diode inhibits accurate capacitance measurements.

The AS measurements for the sample with high

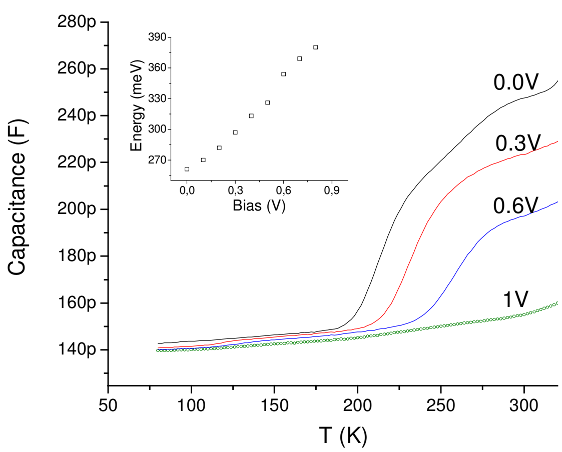

Fig.5. Admittance spectra of the sample with high Boron pretreatment for a measuring frequency 50kHz at different bias conditions. Inset: Arrhenius plot obtained from the admittance spectra.

Boron pretreatment give a significantly different picture. With increasing reverse bias, the position of the capacitance steps shifts strongly towards higher temperatures(Fig.5).

For a bias voltage of 1V, the signal has completely vanished. This is consistent with the observation from the C-V measurements(Fig.6). In the inset of Fig.5,

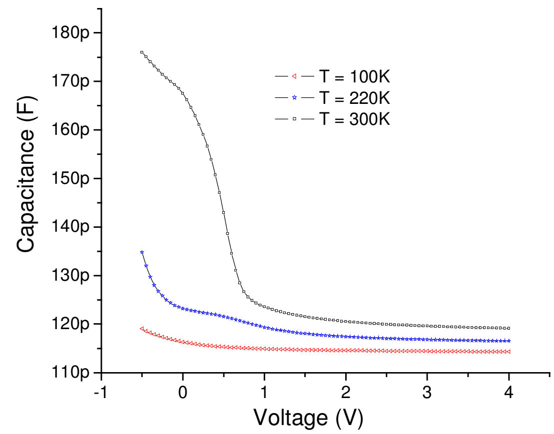

Fig.6. C-V curves at different temperatures for the sample with high Boron pretreatment at a measuring frequency 1MHz.

the activation energies of the E1 peak for the sample with high Boron pretreatment are plotted as a function of reverse bias. With increasing bias voltages the activation energy increases up to a value of about 380meV at 0.8V bias. We can ascribe this energy to the ground states of the islands since the signal vanishes for higher bias voltages.

In the bias range where the linear increase in the activation energy occurs, the behavior of the sample with high Boron pretreatment is different from that of the sample without Boron pretreatment. Rational explanation is the low density of states tentatively causes the strong charge depletion and shift with bias voltage observed in the island structure(high Boron pretreatment) compared to the quantum-well sample(no Boron pretreatment).

4 Conclusion

In conclusion, we have investigated the electrical properties of the self-assembled Ge islands and quantum wells embedded in the p-i-n Si diode structures by means of the capacitance–voltage measurements and admittance spectroscopy. From the C-V measurements, it is obvious that the carrier concentration in quantum wells is remarkably larger than that in quantum dots. By admittance spectroscopy we can devide samples that have quantum well layers from ones that have quantum dots layers. The lack of the Boron pretreatment put obstacles in the way of the nucleation of the quantum dots. The linear increase of the thermal activation energy observed in voltage-dependent admittance spectroscopy for the sample with quantum dots shows that the ensemble of Ge islands has a low, continuous, averaged density of states. Such a peculiar density of states for islands could perhaps serve to design quantum-dot devices as, for example, lateral photodetectors where the absorption wavelength can be continuously tuned by a vertical gate.

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