Self-assembled Ge quantum dots on Si and their applications

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Abstract

Ge quantum dots have been grown on Si by self-assembling in the Stranski–Krastanov growth mode using molecular beam epitaxy. The topics to be addressed are size uniformity control and exact placement of dots. Possible device application discussions show that Ge quantum dots may be used for mid-infrared photodetectors, lasers, resonant tunneling diodes, thermoelectric cooler, cellular automata, and quantum computer, etc.

1. Introduction

Self-assembled Ge quantum dots grown by molecular beam epitaxy (MBE) and chemical vapor deposition (CVD) have attracted a great deal of interest for several years. The dots are known to develop during epitaxial growth in the Stranski–Krastanov growth mode, which begins with layer-by-layer growth followed by island formation. The key reason is the 4.16% mismatch between the Si and Ge lattice constants. The size of the dome-shaped Ge dots (40–80 nm in base diameter and 3–10 nm in height) is in the order of the electron wavelength and thus the discrete energy levels may be observed at reasonable temperatures. The ability to form the energy-quantized islands without any artificial masking and patterning (by self-assembly) and their compatibility with the current Si technology provide a great deal of potentials for device applications.

In this paper, we show experimental works resolving the long-standing issues of self-assembled Ge quantum dots on Si: size control and exact placement of dots. We will also discuss possible applications for these dot arrays.

2. Self-assembled and cooperative Ge quantum dots

Due to the strain related self-assembled dot formation mechanism, the uniformity becomes a real problem before the dots can have any practical applications. On planar Si, the uniformity of the dots has been found to depend critically on the growth parameters, such as growth temperature, growth rates, Ge deposited coverage and holding time at the growth temperature after Ge deposition. For the Ge growth rate of
0.2 Å/s and the Ge coverage of 15 Å, the growth temperature for achieving a high uniformity in the dot size was found to be around 600°C. Fig. 1a shows an AFM image of the highly uniform self-assembled Ge dots grown at 600°C. Fig. 1b is the composed three-dimensional view. The dots are all dome-shaped with the base size and the height of about 70 nm and 15 nm, respectively. The areal density of the dots is about $3 \times 10^9$ cm$^{-2}$ and the height deviation of the dots is about ±3%. The formation of the highly uniform distribution of the Ge dots at 600°C is believed to attribute to the enhanced diffusion [1].

For certain applications, the spatial control of placement of dots becomes very important. In the past, many methods have been attempted, including the use of miscut substrates [2], relaxed buffers [3], etc. It was found recently that the use of selective epitaxial growth (SEG) mesas was extremely successful for forming well-regimented quantum dots [4–6]. Firstly, the facet formation in SEG resulted in narrowing of mesas [7]. The deposition of Ge leads to the formation of periodically regimented dots on top of the ridges of the Si stripe mesas. Fig. 2a shows the 2-D image of the dot arrays. Fig. 2b shows the cross-sectional profiles of the mesas and an array of the dots. Fig. 2c is a three-dimensional AFM image. The average sizes of the Ge dots are about 80 nm wide and 20 nm high, and the period of Ge dots is about 120 nm. The regimented arrangement is the result of cooperative interaction from the neighboring dots caused by the balance of diffusion, the strain energy and the repulsive interaction among the dots. The repulsive interaction comes from the elastic tensile deformation of the substrate by the dots [5,6]. The same principle has also been extended to 2-D cases. Fig. 3 shows an AFM image of 2-D aligned self-assembled Ge dots on the exposed 2-D patterned SEG Si mesas areas. The bright regions are Si mesa networks, which were formed after the SEG. The dark regions correspond to the low region in which the original SiO$_2$ masks were removed for AFM measurements. A 1.6-nm-thick Ge was deposited at a
temperature of 700°C, resulting in one dome-shaped Ge dot on each Si mesa. This 2-D arrangement may find useful application for information processing as will be discussed in the following section.

Multi-layered Ge quantum dot superlattices are very important for some applications such as optoelectronics. An interesting feature observed in the multi-layered structures was that the dots in the upper layers tended to grow on top of the buried ones or there was vertical correlation. Fig. 4 shows a typical cross-sectional high-resolution electron microscopy (HREM) image of a 10-period sample. Each period consisted of 12 Å Ge and 20 nm Si materials and there was an evident vertical correlation. The origin of vertical correlation may be attributed to preferential nucleation due to an inhomogeneous strain field induced by buried dots [8].

3. Novel device applications

3.1. Optoelectronics

For optical applications, the ordering of the dot arrays is not essential but the size uniformity is critical. Firstly, multi-layered Ge quantum dots can be used to fabricate novel quantum dot photodetectors operating in the mid-infrared range. For mid-infrared applications, quantum dots have several advantages over conventional quantum wells. First, the predicted long carrier lifetime in the excited states in Ge quantum dots due to reduced carrier–phonon interactions could improve detector performance [9]. Second, because of their sharp δ-like density of states, the dark current level of quantum dot infrared photodetectors is expected to be low when an appropriate doping level is selected. Another important advantage is the selective rule to enable normal incidence photon detection when the lateral sizes are further reduced [10]. For interband transition, pin diodes using the dots layers to form the i region may be used for 1.5 μm fiber optics applications.

Efficient photo-emitters (LEDs) and perhaps Ge lasers might be even possible using Ge quantum dots. Multi-layered Ge dot superlattices may be used as a gain media in which interband transitions in indirect semiconductors like Si and Ge are assisted by phonons to make up the momentum difference between the initial and final states. Furthermore, due to phonon confinement in a quantum dot, phonons with the desired momentum can be designed by the dot size. In addition, as both quantum dot size and inter dot distance...
are comparable with the phonon wavelength, quantum dot superlattices may be used to further control the phonon group velocity and used as a phonon filter. Thus one may be able to invoke phonon mediation to enhance interband optical transitions and Ge quantum dots may be used to achieve phonon-assisted lasers. A new field of phonon engineering may emerge.

3.2. Thermoelectricity

In order to fabricate a high efficient solid-state refrigerator, researchers have studied for decades to look for high figure-of-merit thermoelectric materials. Previously, quantum well structures of SiGe/Si have been shown to have an increased figure-of-merit due to the change of the density of states of electrons to increase Seebeck coefficient and to reduce thermal conductivity at the same time due to the reduced phonon transport [11,12]. Ge quantum dot superlattices may have further improvements and may be used to fabricate novel thermoelectric devices for the following reasons. Firstly, it is determined that quantum dots can effectively confine phonons [13] or even strongly scatter phonons [14], resulting in a further reduction of the thermal conductivity. Meanwhile, quantum dots have a δ-like density of states due to quantum confinement of electrons, which in turn increases thermoelectric power factor and thus the figure-of-merit. Indeed, quantum dots may constitute a better class of the “phonon-blocking electron-transmitting” materials compared with alloys, quantum well superlattices, and wires. The thermoelectric devices may be fabricated for improved devices.

3.3. Electronic applications

The Moore’s law demands the continuous increase of functionality per unit area and cost. The approach that we have been following is the scaling down of the physical size. As we approach the physic size limit due to either the technology or the cost of fabrication, alternate means of increasing the functionality needs to be pursued. One approach is to increase the functionality by integrating quantum devices. For example, tunnel diodes may be incorporated into CMOS to reduce the device account of the functional cluster, e.g., reducing the number of transistor for a SRAM from 6 to 1 [15]. Ge quantum dots could also be used to fabricate improved tunneling diodes with a reduced valley current density because of the delta density of states [16]. For this purpose, the large valence band offset in the Si/Ge dots system may be taken advantage of. The indirect bandgap and the heavy masses of electrons do not make Si an ideal candidate for fabrication of resonant tunneling diodes. But, Ge dots embedded at the proper position within the p–n junction are expected to enhance the tunneling current considerably in Esaki (Zener) tunneling of electrons through an empty valence band in the Ge dots into the p-type region of the Si side. Many similar examples may be possible.

Likewise, well organized, particularly, 2-D arranged Ge quantum dots can be used to realize novel cellular automata, a class of device/circuit which may minimize the problems of interconnect in today’s CMOS circuits. 2-D quantum cellular automata require a 2-D array orderly arranged in space. Each cell of the array has a well-defined state representation, for example, by the electron number in the cell. To achieve low power consumption, high-speed operation and high density, the size of cells should be below 100 Å according to the single electron model. The self-registered Ge quantum dot growth is shown to produce a high quality 2-D array using a patterned substrate of a much larger feature size (as shown in Fig. 3). These arranged Ge quantum dots may be used either directly as quantum subsystem or as micromask to integrate more complicated quantum structures into the cell, in which a simple set of rules in updating the state may be used for imaging processing such as edge determination of images. This method is not the only way but a promising path to fabricate 2-D quantum cellular automata.

3.4. Quantum information applications

Lastly in this subsection, we believe that Ge quantum dots have potential applications in quantum computer. The basic engineering
prerequisites for a successful implementation of a quantum computation device are: creation of the quantum memory unit (qubit) with decoherence time significantly less than computation cycle [17], unitary rotations of the qubits and ability to control interaction between the qubits [18].

There are several physical reasons why the Ge quantum dots are very promising for the application in quantum computing compared with other designs proposed recently in this intensively developing research area [19–23]. Firstly, there are some theoretical evidences [24,25] that certain germanium-rich SiGe alloys give the type I alignment of the conduction band with coherently strained Ge grown on top. Thus, electrons can be effectively localized in the quantum dots to serve as qubits. Electron trapped into the dot will be restricted in its orbital motion to the low-angular momentum states that will drastically suppress the spin–orbit interaction [26], thereby effective decoupling of the electron spin from the environment can be achieved. Secondly, because of the spatial confinement, the electron g-factor is a sensitive function of the electric field [27] and this concept would allow an efficient tuning of the electron spin in and out of resonance by an applied local electric field. Thirdly, the chemical-impurities concentration is a few orders lower than in III–V compounds and, finally, most of the Si and Ge isotopes do not have a net nuclear magnetic moment from paramagnetic centers, which make these materials almost superb in creating a decoherence free environment for the electron spin. In particular, the absence of the dipole–dipole interaction between the electron and nuclear spins results in the spin-relaxation time significant increase in comparison with the III–V compound materials [28,29]. These advantages suggest that Ge quantum dots will have a great deal potentials in quantum information processing applications.

4. Summary

We have discussed the process of the growth of highly uniform Ge quantum dots and cooperative assembly Ge quantum dot arrays on Si. The highly uniform dots and well-regimented dots may find applications in infrared photo-detection, lasing, thermoelectric refrigeration, resonant tunneling, quantum information processing and so on.

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References