Observation of inter-sub-level transitions in modulation-doped Ge quantum dots

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(Received 26 April 1999; accepted for publication 27 July 1999)

The inter-sub-level transitions in modulation-doped Ge quantum dots are observed. The dot structure is grown by molecular-beam epitaxy, and consists of 30 periods of Ge quantum dots sandwiched by two 6 nm boron-doped Si layers. An absorption peak in the midinfrared range is observed at room temperature by Fourier transform infrared spectroscopy, which is attributed to the transitions between the first two heavy-hole states of the Ge quantum dots. This study suggests the possible use of modulation-doped Ge quantum dots for improved infrared detector applications. © *1999 American Institute of Physics.* [S0003-6951(99)01338-8]

Optical properties due to inter-sub-level transitions in zero-dimensional quantum dot systems are attracting much attention. This interest is primarily stimulated by the anticipation that the success achieved in using quantum well structures in novel infrared photodetectors and imaging focal plane arrays may be further extended to the use of quantum dots for these devices. For this application, quantum dots have several advantages as compared to quantum wells. First, a predicted long carrier lifetime in the excited states in quantum dots due to reduced carrier phonon interaction may further enhance detector performance.[1–3] It is also possible to have normal incidence photoexcitation and thus detection.[4,5] Because of their sharp δ-like density of states, the dark current levels of quantum dot infrared photodetectors are expected to be low when an appropriate doping level is used. To date, most of the work in this field is based on optical transitions of electrons within the conduction band in III–V quantum dot structures.[4–9] Recently, we have reported the observation of inter-sub-level absorption of holes in boron-doped multiple Ge quantum dots.[10] We now report on the inter-sub-level absorption observed in modulation-doped *p*-type Ge quantum dots. The fact that the separation of donors and holes causes bandbending, which influences the band structure and the energy levels in the quantum dots, monitors the hole inter-sub-level absorption further compared with well-doped quantum dots.

The sample is grown using a solid-source molecular-beam epitaxy (MBE) system. A Si (100) wafer with a resistivity of 18–25 Ω cm is used as a substrate and cleaned using a standard Shiraki cleaning method followed by *in situ* thermal cleaning at 930 °C for 15 min. The substrate temperature is maintained at 600 °C during the epitaxial growth. The nominal growth rates are 1 and 0.2 Å/s for Si and Ge, respectively. Boron doping is achieved by sublimation of boron from a Knudsen cell. The sample consists of a 200 nm undoped Si buffer layer, 30 periods of Ge quantum dots sandwiched between two 6 nm boron-doped Si layers, and a 50 nm undoped Si cap layer. The doping density in the Si layers is as high as $5\times10^{18}\,\mathrm{cm}^{-3}$. Figure 1 shows a cross-sectional transmission electron microscopy (TEM) image of the sample. The Ge dots can be seen as some obscure, dark features distributed in the Ge wetting layer dark stripes. One of reasons for the obscurity is that Ge interdiffuses a lot to form the SiGe alloy underneath the dots and on top of them because of high growth temperature (600 °C). This is verified by performing Raman scattering measurements. The result is shown in Fig. 2. The spectra are recorded from the dot sample and an identical Si substrate using the same back-scattering configuration with the identical accumulation time. The appearance of the Si–Ge peak at 403 cm^{-1} in the top sample spectrum implies the formation of the SiGe alloy in the wetting layers as well as in the interfaces between the dots and Si layers on top of them. In addition, the appearance of a local Si–Si vibrational peak at 440 cm^{-1} suggests the existence of strain in Si underneath the dots induced by the formation of Ge dots. In the bottom substrate spectrum, besides a strong Si–Si vibrational mode at 520 cm^{-1}, a small peak is found at 303 cm^{-1} (the intensity is not comparable with that of the Ge–Ge mode at 301 cm^{-1} in the sample spectrum), which arises from the second-order Si–Si acous-

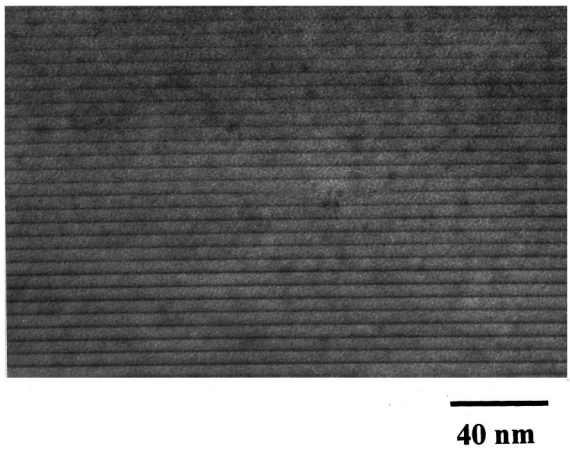

FIG. 1. Cross-sectional TEM image of the sample. The quantum dots can be seen as dark features distributed in the Ge wetting layer dark stripes.

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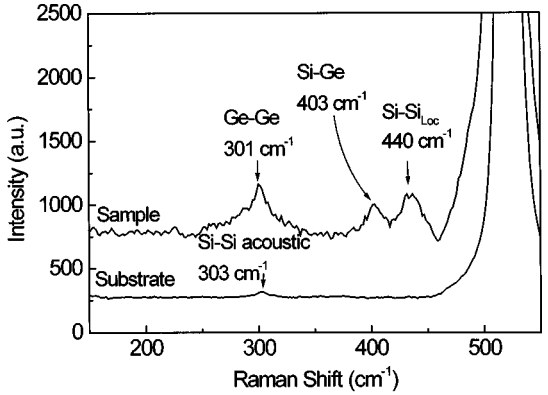

FIG. 2. Typical Raman spectrum of the sample. Ge–Ge, Si–Ge, and local Si–Si vibrational peaks can be seen at 301, 403, and 440 cm^{-1}, respectively. In the substrate spectrum, a small peak at 303 cm^{-1} arises from the second-order Si–Si acoustic phonons.

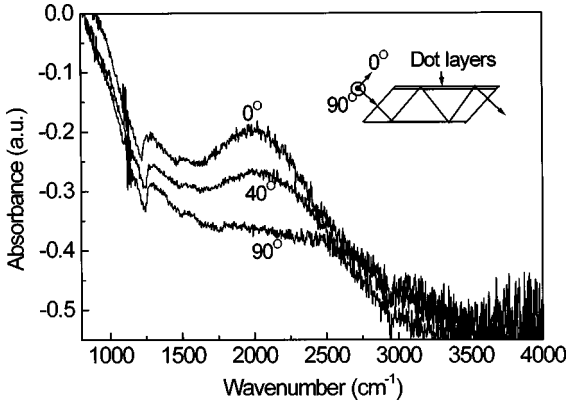

FIG. 4. Polarization-dependent absorption spectra of the sample. The decrease of the absorbance with increasing polarizer angle is due to the reduction of the component of the photon polarization along the growth direction.

tic phonons. In order to obtain more structural data of the dots, atomic force microscopy (AFM) is used to examine a similar sample without the cap layer. Details can be found elsewhere.[11] Combined with these results, we conclude that the Ge dots in our sample have a typical height of 25 Å. The nonuniformity of the dot size is estimated to be 10%. The areal density of the dots is around $10^9\ cm^{-2}$.

The inter-sub-level transitions in the dots can be verified by performing Fourier transform infrared spectroscopy (FTIR) measurements. The infrared absorption spectra of the sample are taken at room temperature using a Nicolet spectrometer. A waveguide structure of 10 mm×5 mm in size is prepared with a polished backside and polished 45° facets in order to enhance the absorption. A Si substrate waveguide with the same dimension is used as the reference. Figure 3 shows the measured absorption spectrum with unpolarized infrared light. An absorption peak is found at 2004 cm^{-1}, which is believed to come from the inter-sub-level transition of holes in the Ge quantum dots. The full width at half maximum (FWHM) of 62 meV is considerably larger than the inter-sub-level peak width observed in the InGaAs/GaAs quantum dot superlattice (~13 meV).[1] Obviously, the size nonuniformity of quantum dots may be a contributing factor. Additionally, the nonparabolicity of the hole bands may play a strong role in the broadening of the absorption peaks as was observed in the quantum well case.[12] Background absorption mainly associated with the free carriers can be observed as a monotonously increasing absorption towards low energy.

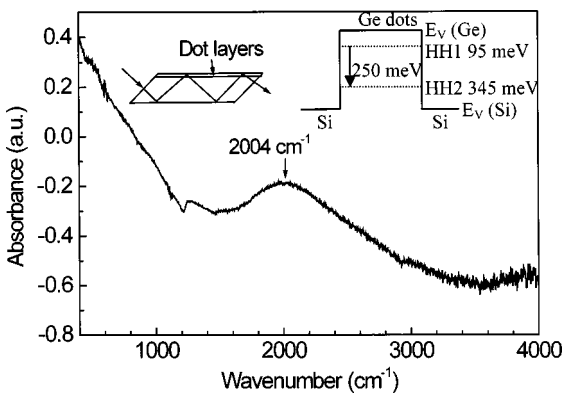

FIG. 3. FTIR absorption spectrum of the sample. No polarization of the incident infrared light is employed. An absorption peak at 2004 cm^{-1} is due to the inter-sub-level absorption in the Ge quantum dots.

Previously, we observed an absorption peak at 2000 cm^{-1} for multiple boron-doped Ge quantum dots with a height of 40 Å.[10] We treated those dots as quantum boxes and attributed the absorption peak to the transitions between the first two heavy-hole states. Here, an inter-sub-level absorption peak with almost the same peak position is observed at a reduced dot size (25 Å in height). This could arise from the fact that the present dots are modulation doped, and thus, the band structures are affected by the separation of donors and holes. In order to evaluate the transitions in the present dots, a finite-barrier model is used to determine the energies. For simplicity, we do not consider valence-band mixing as well as dielectric screening. In addition, because the lateral dimensions of the Ge dots are usually much larger than their heights, we omitted the quantum-confinement effect in the lateral direction. Assuming $\xi=\sqrt{-2m_BE/\hbar^2}$ and $\eta=\sqrt{2m_B(V_0+E)/\hbar^2}$, where E is the allowed energies in the dots, V_0 is the valence-band offset between the Si barriers and the Ge dots, and m_A and m_B are the effective masses of the holes in the Ge dots and Si barriers, respectively. The allowed energies can be evaluated as follows:[13]

$$(\eta/m_A)\tan(\eta a/2)=\xi/m_B$$

and

$$(\eta/m_A)\tan^{-1}(\eta a/2)=-\xi/m_B,$$

where ''a'' is the typical height of the dots. The effective masses in the dots used in the calculations are 0.30 and 0.044 m_0 for the heavy and light holes, respectively. In addition, it is important to note that the present Ge/Si system is a type-I structure. Thus, the largest possible barrier V_0 for the heavy and light holes is the band-gap difference between the Si and Ge (1.12–0.67 eV=0.45 eV) if we assume the entire band offset occurs in the valence band.[14] The calculated results are schematically shown in the top-right inset of Fig. 3, indicating that there are no occupied light-hole levels, while there are two heavy-hole energy levels at 95 and 345 meV. The energy separation between these two levels is 250 meV, which is quite close to the measured peak energy of 249 meV (2004 cm^{-1} peak in Fig. 3). Generally, there should not

be such good agreement by using the simple finite-barrier model. In other words, suppose an ideal model regarding the size effect can be used, the calculated level spacing would be more or less different from the measured peak energy. Thus, other effects, such as bandbending due to the separation of the donors and holes, strain, dielectric screening, and valence-band mixing may play some role in influencing the level spacing in the modulation-doped Ge dots.

The nature of the observed inter-sub-level transitions can be confirmed further by performing polarization-dependent FTIR experiments. Figure 4 shows the polarization dependence of the 2004 cm^{-1} inter-sub-level peak. As shown schematically in the inset of the Fig. 4, the 0° polarization angle corresponds to a 50% component of the incident infrared light polarized along the growth direction of the structure, while the 90° polarization angle is defined as being parallel to the plane of layers. It can be seen that the absorption amplitude decreases with an increase in the polarization angle and the trend behaves like that of the quantum well-like feature.[12] This is because the lateral dimensions of the present dots are much larger than their heights. Accordingly, the quantum confinement along the growth direction is much larger than that in the lateral direction.

In summary, we report the inter-sub-level absorption of modulation-doped Ge quantum dots. Absorption in the mid-infrared range is observed by FTIR, and is attributed to the transition between the first two heavy-hole states. This study provides an impetus to fabricate improved infrared detectors using modulation-doped Ge quantum dots.

The authors would like to thank Professor K. N. Tu and Chih Chen for the TEM measurements and Dr. Y. S. Tang for assistance in the Raman scattering measurements and useful discussions. The work was in part supported by the National Science Foundation (DMR-9520893), ARO (DAAG55-98-1-0358), and ONR (MURI on thermoelectric).

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[14] This number is estimated based on unstrained Ge dots and underlying Si. The presence of strain and the separation of donors and carriers change the band gaps of Si and Ge, and thus, the corresponding band offset.