

## Intersubband absorption in boron-doped multiple Ge quantum dots

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The intersubband absorption in self-assembled boron-doped multiple Ge quantum dots is observed. The structures used consist of 20 periods of boron-doped Ge dot layers and undoped Si barriers. The infrared absorption as a function of wavelength is measured by Fourier transform infrared spectroscopy using a waveguide geometry. Absorption peaks in the mid-infrared range have been observed, which are attributed to the transitions between the first two heavy hole states of the Ge quantum dots. The polarization dependence measurement is used to study the nature of the transitions. This observation suggests the possible use of multiple Ge quantum dots for infrared detector application. © 1999 American Institute of Physics. [S0003-6951(99)00702-0]

Intersubband transition in quantum confined semiconductor nanostructures is a subject of interest both for a fundamental physics study and for the development of infrared photodetectors and lasers. Previously, quantum well structures and detectors have been studied extensively because of the available mature epitaxial techniques such as molecular beam epitaxy (MBE) and ultrahigh vacuum chemical vapor deposition.<sup>1-4</sup> Compared with two-dimensional quantum well structures, the intersubband absorption in the zero-dimensional quantum dot structures has advantages in optical applications due to their sharp delta-like density of states, the reduced intersubband relaxation times and thus lower detector noises in these nanostructures.<sup>5,6</sup> With the recent success in fabricating high quality quantum dots by the Stranski-Krastanow growth process in MBE,<sup>7-9</sup> it is timely to examine the intersubband optical transitions of these structures. Most of the work to date is based on intersubband absorption of electrons of III-V based quantum dot structures. For example, infrared absorption has been reported for charged InGaAs quantum dots for wavelengths  $>20 \mu\text{m}$ ,<sup>10</sup> and for doped InAs dots in the range of  $10\text{--}20 \mu\text{m}$ ,<sup>11</sup> respectively. Mid-infrared photoconductivity at around  $3 \mu\text{m}$  has also been studied for delta-doped InAs/AlGaAs quantum dots for subbands to continuum transitions.<sup>12</sup> To date, limited work has been done in SiGe-based Ge quantum dot structures. The fact that there is a large valence band offset of the zero-dimensional Ge/Si system, as well as the small hole effective mass, favors the hole intersubband absorption for mid-infrared applications.<sup>13</sup> Moreover, another key advantage of the epitaxial Ge quantum dot structures and thus infrared detectors is the possibility of monolithic integration with the mature Si signal processing electronics.

In this letter, we report the observation of the intersubband absorption in boron-doped multiple layers of Ge quantum dots. The samples are grown using a solid source MBE system. First, Si (100) wafers with the resistivity of  $14\text{--}22 \Omega \text{ cm}$  are used as substrates. After a standard Shiraki's cleaning procedure, the substrates are introduced into the MBE system immediately. The protective oxide layer is re-

moved by subsequently heating the substrate to  $930^\circ\text{C}$  for 15 min. The substrate temperature is maintained at  $650^\circ\text{C}$  during the epitaxial growth. The nominal growth rates are 1 and  $0.2 \text{ \AA/s}$  for Si and Ge, respectively. With this condition, a 200 nm undoped Si buffer layer is grown first, followed by 20 periods of thin heavily boron-doped Ge quantum dot layers sandwiched with two 6 nm undoped Si films. The schematic of a typical heterostructure is shown in Fig. 1. In this work, the samples (A, B and C) with different Ge layer thicknesses are prepared to study the size dependence of the subband energy. Similar samples without the last Si barrier (with Ge quantum dots grown on the surface) are examined with atomic force microscopy (AFM) showing typical base dimensions of 420, 450 and  $480 \text{ \AA}$ , and heights of 40, 45 and  $100 \text{ \AA}$ , for samples A, B and C, respectively. The nonuniformity of the dot size is estimated to be  $\pm 10\%$ . The area densities of the dots for samples A, B and C are  $1 \times 10^8$ ,  $2 \times 10^8$ , and  $2 \times 10^8 \text{ cm}^{-2}$ , respectively.

The infrared absorption spectra of the samples are taken at the room temperature using a Fourier transform infrared (FTIR) spectrometer. Waveguide structures of  $10 \text{ mm} \times 5 \text{ mm}$  in size are prepared with polished backsides and polished  $45^\circ$  facets for the measurement in order to enhance the absorption. A beam condenser is used to focus the infrared

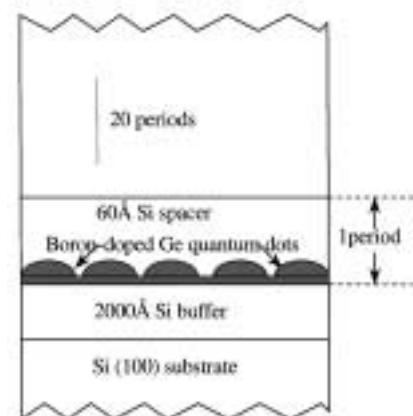


FIG. 1. Schematic of multiple Ge dots for FTIR absorption spectra measurement.

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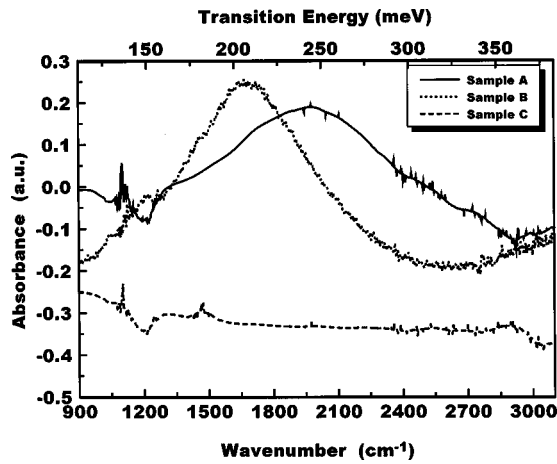


FIG. 2. FTIR absorption spectra for samples A, B and C taken at room temperature. Background spectra have been subtracted.

beam onto the waveguide. An infrared polarizer is placed in the path of the infrared beam to probe the polarization dependence of the absorption process. A Si substrate waveguide with the same dimensions is used as the reference.

Figure 2 shows the measured absorption spectra of the samples A, B and C at the  $0^\circ$  polarization angle (i.e., electric field having a component in the growth direction as described in the following). For sample A, absorption peaks are found at near  $2000\text{ cm}^{-1}$  ( $5\ \mu\text{m}$ ) and  $1350\text{ cm}^{-1}$  ( $7.4\ \mu\text{m}$ ), which are attributed to intersubband transitions in the Ge quantum dots and the Ge wetting layer, respectively. The full width at half maximum (FWHM) of the absorption peak at  $5\ \mu\text{m}$  for the sample A is about 100 meV, and is considerably larger than the intersubband peak width observed in InGaAs/GaAs quantum dot superlattice ( $\sim 13\text{ meV}$ ).<sup>14</sup> The size non-uniformity of quantum dots is a possible factor. Another reason is that the nonparabolicity of the hole bands can play a strong role in the broadening of the absorption peaks as was observed in the quantum well case.<sup>2,3,13</sup> Similar to sample A, absorption peaks are found at  $1650\text{ cm}^{-1}$  ( $6\ \mu\text{m}$ ) and  $1350\text{ cm}^{-1}$  ( $7.4\ \mu\text{m}$ ) for sample B, which are again due to transitions in the Ge quantum dots and the Ge wetting layer, respectively. For sample C, however, only one absorption peak near  $7.4\ \mu\text{m}$  is found, which is believed to be due to the absorption in the Ge wetting layer. The vanishing intersubband absorption in these Ge dots is due to the large size of Ge dots of sample C ( $100\ \text{\AA}$  in height), and thus the energy difference between two hole bound states is too small to be observed in the absorption in the investigated energy range, beyond which free carrier absorption tends to obscure the measurement of intersubband transitions. The almost same absorption peak position in three Ge wetting layers for samples A, B and C is due to the fact that the thicknesses of wetting layers (usually  $3\text{--}6\ \text{\AA}$ ) of the samples are about the same under almost the same growth conditions (for example, growth temperature).<sup>15</sup> From Fig. 2, all three samples have peaks near  $1100$  and  $1450\text{ cm}^{-1}$ , which are mainly due to the strong infrared absorption by  $\text{SiO}_2$  and water bands in the spectral range of interest.

The observed intersubband transitions in the Ge dots can be compared with the calculated subband energies. Here, we assume a Ge dot is a simple infinite barrier box, and do not

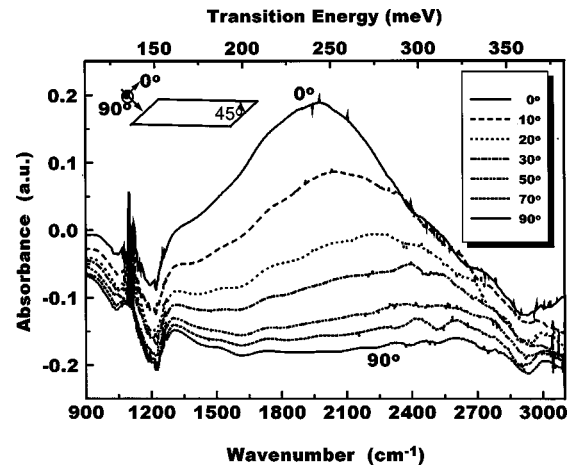


FIG. 3. Polarization dependent absorption spectra of sample A taken at room temperature. The decrease of the absorbance with the increasing polarizer angle is due to the reduction of the component of the photon polarization along the growth direction.

consider exciton-like effects as well as depolarization effects.<sup>13</sup> Thus, the allowed energies in the dot can be evaluated precisely as follows:

$$E_{n,k,l} = \frac{\pi^2 \hbar^2}{2m^*} \left( \frac{n^2}{L_X^2} + \frac{k^2}{L_Y^2} + \frac{l^2}{L_Z^2} \right) \quad n, k, l = 1, 2, 3, \dots, \quad (1)$$

where  $m^*$  is the Ge hole effective mass. The effective masses used for calculation are  $0.30 m_0$  and  $0.044 m_0$  for the heavy and light holes, respectively.  $L_X$  and  $L_Y$  are base dimensions, while  $L_Z$  is the height of the dots. For sample A, the first two terms of the equation are omitted because  $L_X$  and  $L_Y$  ( $42\text{ nm}$ ) are much larger than  $L_Z$  ( $4\text{ nm}$ ). The calculated results show that there are two heavy hole bound states at 78 and 311 meV while there are no occupied light hole bound states. This can be easily understood since the largest possible band offset for the light and heavy holes is the band gap difference between the Si and Ge ( $1.12 - 0.67 = 0.45\text{ eV}$ )<sup>16</sup> if we assume the entire band offset is consumed in the valence band. The ground state of the light hole can only exist at the top of the Si barrier potential or higher due to the small effective mass and small dot size, and there can be no occupied bound light hole state. The energy separation between the first two heavy hole states is 233 meV, which is close to the measured peak energy of 247 meV ( $5\ \mu\text{m}$  peak). Similar calculation has been done for sample B and the calculated energy separation of 184 meV is also close to the measured peak energy of 205 meV ( $6\ \mu\text{m}$  peak). The difference between the observed and calculated energies may come from the valence band mixing as well as the depolarization and exciton-like shifts. In other words, the observed absorption peaks of  $5$  and  $6\ \mu\text{m}$  are due to the transitions between the first two heavy hole bound states.

In order to confirm the nature of intersubband transitions in the present Ge quantum dots further, the polarization dependence of the intersubband peaks is performed. Figure 3 shows the polarization dependence of the  $5\ \mu\text{m}$  peak of sample A. Here, the  $0^\circ$  polarization angle corresponds to a 50% component polarized along the growth direction of the structure, while the  $90^\circ$  polarization angle is defined as being parallel to the plane of layers. The absorption of the Ge

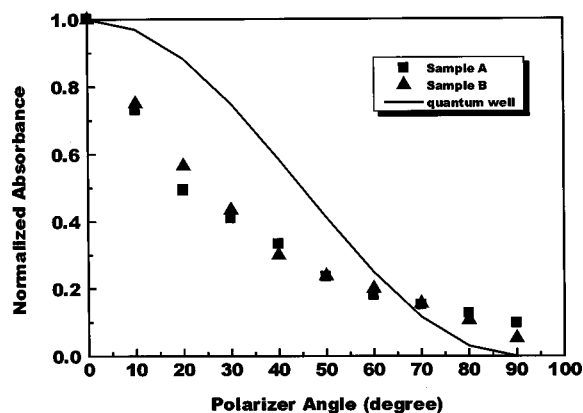


FIG. 4. Polarization angle dependence of the absorption strength. The measured values at the 5  $\mu\text{m}$  peak for sample A and at the 6  $\mu\text{m}$  peak for sample B are compared with the  $\cos^2 \theta$  dependence of quantum wells on Si (100) substrates.

quantum dots exhibits a maximum at the 0° polarization angle, which corresponds to the direction of the largest confinement in the dots. The absorption strength decreases as the polarization angle increases. Similar result is obtained for the 6  $\mu\text{m}$  peak of sample B. Figure 4 shows the polarization angle dependence of the absorption spectra. The solid line is a typical polarization dependence on polarization angle  $\theta$  for quantum wells grown on Si (100) substrates, which is shown to vary with  $\cos^2 \theta$ , in agreement with the well-known feature of intersubband transitions. The solid symbols are the polarization dependence data of Ge quantum dots at the 5  $\mu\text{m}$  peak for sample A and at the 6  $\mu\text{m}$  peak for sample B, respectively. It can be seen that the absorption strength decreases with the increase of the polarization angle and the trend of the data behaves like the quantum well-like feature. The similar result of the quantum well-like polarization dependence was reported by Sauvage *et al.* for the *n*-doped InAs/GaAs quantum dot system.<sup>17</sup> This is due to the fact that multiple quantum dots are usually flattened in the sandwiched spacer layers under most growth conditions.<sup>18</sup> These dots have relatively large base dimensions even though the height is very small. Accordingly, the confinement is strong along the growth direction but weak in the lateral directions. Thus, the polarization dependence of the intersubband peaks in these dots is similar to that in the quantum wells.

In summary, we have reported the intersubband absorp-

tion in multiple self-organized Ge quantum dots. For boron-doped Ge dots, the intersubband transition in the quantum dots has been observed in the midinfrared range, which is attributed to the transition between the first two heavy hole states. The transitions have also been found polarized along the growth axis of the dots, and the absorption strength decreases as the polarization angle increases. The success of growth of boron-doped Ge quantum dots and the observation of the intersubband transitions suggest that Ge quantum dots may be further developed for mid-infrared detectors.

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- <sup>1</sup>L. West and S. Eglash, *Appl. Phys. Lett.* **46**, 1156 (1985).
- <sup>2</sup>S. K. Chum, D. S. Pan, and K. L. Wang, *Phys. Rev. B* **47**, 15638 (1993).
- <sup>3</sup>R. P. G. Karunasiri, J. S. Park, and K. L. Wang, *Appl. Phys. Lett.* **59**, 2588 (1991).
- <sup>4</sup>P. Kruck, M. Helm, T. Fromherz, G. Bauer, J. F. Nützel, and G. Abstreiter, *Appl. Phys. Lett.* **69**, 3372 (1996).
- <sup>5</sup>H. Benisty, C. M. Sotomayor-Torres, and C. Weisbuch, *Phys. Rev. B* **44**, 10945 (1991).
- <sup>6</sup>U. Bockelmann and G. Bastard, *Phys. Rev. B* **42**, 8947 (1990).
- <sup>7</sup>K. H. Schmidt, G. Medeiros-Ribeiro, M. Oestreich, P. M. Petroff, and G. H. Dohler, *Phys. Rev. B* **54**, 11346 (1996).
- <sup>8</sup>J. Tersoff, C. Teichert, and M. G. Lagally, *Phys. Rev. Lett.* **76**, 1675 (1996).
- <sup>9</sup>K. Mukai, N. Ohtsuka, and M. Sugawara, *Appl. Phys. Lett.* **70**, 2416 (1997).
- <sup>10</sup>H. Drexler, D. Leonard, W. Hansen, J. P. Kotthaus, G. Medeiros-Ribeiro, and P. M. Petroff, *Phys. Rev. Lett.* **73**, 2252 (1994).
- <sup>11</sup>J. Phillips, K. Kamath, X. Zhou, N. Chervela, and P. Bhattacharya, *Appl. Phys. Lett.* **71**, 2252 (1994).
- <sup>12</sup>K. W. Berryman, S. A. Lyon, and M. Segev, *Appl. Phys. Lett.* **70**, 1861 (1997).
- <sup>13</sup>K. L. Wang and R. P. G. Karunasiri, in *Semiconductor Quantum Wells and Superlattices for Long-Wavelength Infrared Detectors*, edited by M. O. Manasreh (Artech, 1993).
- <sup>14</sup>D. Pan, Y. P. Zeng, M. Y. Kong, J. Wu, Y. Q. Zhu, C. H. Zheng, J. M. Li, and C. Y. Wang, *Electron. Lett.* **32**, 1726 (1996).
- <sup>15</sup>H. Sunamura, S. Fukatsu, N. Usami, and Y. Shiraki, *J. Cryst. Growth* **157**, 265 (1995).
- <sup>16</sup>The number was estimated based on unstrained Ge dots and underlying Si. The presence of strain as evidenced in, for example, Ref. 13, changes the bandgaps of Si and Ge, and thus the band offset.
- <sup>17</sup>S. Sauvage, P. Boucaud, F. H. Julien, J.-M. Gerard, and V. Thierry-Mieg, *Appl. Phys. Lett.* **71**, 2785 (1997).
- <sup>18</sup>S. Schierker, O. G. Schmidt, K. Eberl, N. Y. Jin-Phillipp, and F. Phillipp, *Appl. Phys. Lett.* **72**, 3344 (1998).