Type-I optical emissions in Ge/Si quantum dots

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Formation of carbon-induced germanium dots
Type-I optical emissions in Ge/Si quantum dots

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The authors studied the optical emission of Ge/Si quantum dots under externally applied biaxial stress using samples grown at different temperatures varying from 430 to 700 °C. The optical emission energy of samples grown at low temperatures is rather insensitive to the applied external stress, consistent with the type-II band alignment. However, for samples grown at high temperatures we observed a large blueshift, which suggests type-I alignment. The result implies that recombination strength can be controlled by the growth temperature, which can be useful for optical device applications. © 2007 American Institute of Physics. [DOI: 10.1063/1.2764113]

Ge/Si self-assembled quantum dots are promising systems for optoelectronic applications because their discrete electronic states can be modulated by dot size and strain, giving transition energies in a spectral range that is widely used for optical communication. The band alignment at the Si/Ge interface was the object of a long controversy. It is now generally accepted that Ge/Si quantum dots present type-II band alignment at the interfaces, where holes are confined in the Ge dot, while the electrons are confined in the Si layer surrounding the dot. Nevertheless, recent work by various authors shows evidence of photoluminescence shift in the PL peak with increasing strain.
growth temperatures, respectively, taken at progressively higher values of biaxial strain. All samples exhibit broad optical emission bands in the absence of an external strain. Under biaxial tensile strain, the emission bands practically remain at the same energy for samples grown at 480 and 530 °C and present a large blueshift for samples grown at 580 and 700 °C. The energy shift of the PL peak position versus biaxial tensile strain of all samples is plotted in Fig. 2(c). We also varied the laser intensity, from ~8 to 160 W/cm²; however, we observed the same behavior shown in Fig. 2(c). This strained-induced energy shift can be estimated using a linear deformation potential theory. We used the values of the parameters given in Ref 1. The type-I optical emission corresponds to the recombination of electron (in Δ₃) and heavy hole both in the Ge dot and we can easily calculate it using the values of the parameters for the Ge. On the other hand, for the type-II emissions the electron (in Δ₂ in Si) and heavy hole (in Ge) involve different materials. Since the hydrostatic deformation potential is obtained experimentally only for its difference, it cannot be described by the simple model used here for type-II transition, and thus it is an opened parameter. However, we used in this work the values of parameters for the Si (for Ge, the energy shift is very similar) in order to analyze the qualitative behavior. The theoretical curves are plotted in Fig. 2(c), where the solid and dashed lines indicate the type-I and type-II energy shifts, respectively. The figure shows that the two samples grown at higher temperatures (solid symbols) exhibit shifts compatible with type-I behavior, while the two samples grown at 430 and 480 °C (represented by open symbols) exhibit type-II behavior. Better quantitative agreement for type-II shift could be attained by adjusting the values of the deformation potentials or using a more complex model. However, the trend indicated in Fig. 2(c) clearly defines which sample shows either type-I or type-II behavior.

Changing the growth temperature, as shown in Table I, basically changes the dot sizes and densities. However, it should also affect intermixing effects, which result in a different Ge distribution in the dot and, consequently, different built-in strain. Strain relaxation in the dot can also depend on the dot size. Since the estimated value for the conduction band offset is quite small (~40 meV for unrelaxed pure Ge/Si interfaces) it may be sensitive to the distribution of the Ge content and the strain in the dot. All these factors can result in either type-I or type-II recombination.

### Table I. Description of the samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Growth temp. (°C)</th>
<th>Density (cm⁻³)</th>
<th>Diameter (nm)</th>
<th>Height (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>700</td>
<td>1.5 × 10¹⁰</td>
<td>200</td>
<td>20–25</td>
</tr>
<tr>
<td>Sample 2</td>
<td>580</td>
<td>7 × 10¹⁰</td>
<td>60–70</td>
<td>~11</td>
</tr>
<tr>
<td>Sample 3</td>
<td>480</td>
<td>1.4 × 10¹¹</td>
<td>~30</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Sample 4</td>
<td>430</td>
<td>1.5 × 10¹¹</td>
<td>20–25</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

In summary, we observed that the optical emissions in Ge/Si QDs are quite sensitive to the external strain when the quantum dot is grown at low or high temperature. The result suggests that the growth temperature plays an important role on the carrier distribution, resulting in a type-I or type-II recombination. Thus, growth temperature can be used as a parameter to manipulate the transition oscillator strength in optical devices.

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