A Novel Approach to Evaluate the Carrier Effective Mass in GeSi Quantum Dot Structure

Zheng YANG 1,†, Yi SHI 1,*, Jian-Lin LIU 2, Bo YAN 1, Rong ZHANG 1, You-Dou ZHENG 1, Kang-Long WANG 3

1 Department of Physics, Nanjing University, Nanjing 210093, China
2 Department of Electrical Engineering, University of California at Riverside, CA92521, USA
3 Department of Electrical Engineering, University of California at Los Angeles, CA90095, USA

Email: † yangzenith@263.net; * yshi@nju.edu.cn

Abstract—Carrier effective mass in the self-assembled GeSi quantum dots (QDs) grown by a solid-source molecular beam epitaxy (MBE) system has been studied with temperature-dependent photoluminescence (PL) and Raman scattering measurements. The temperature-dependence of the PL was fitted by the combination of Arrhenius and Berthelot type functions, from which a novel approach to evaluate the carrier effective mass has been proposed.

I. INTRODUCTION

GeSi material system greatly extends the performance and versatility of Si-based semiconductors. In particular, the self-assembled GeSi QDs by the Stranski-Kranstanow (S-K) growth mode have attracted much attention. GeSi QDs have been successfully fabricated to devices, such as resonant tunneling diodes [1] and photodetectors at 1.5 µm [2]. Moreover, it has been theoretically predicted that an indirect-to-direct conversion of the optical transition of GeSi QDs would occur whenever the sizes of the QDs were small enough [3]. To study the electrical and optical properties of the GeSi QDs is very important for their applications in microelectronics and optoelectronics. Although lots of related work has been made in recent years, little has been done on the carrier effective mass in the GeSi QDs. In this report, a novel approach to estimate the carrier effective mass in the GeSi QDs based on the temperature-dependent PL spectra has been proposed. And the values of the carrier effective masses in the GeSi QDs have been analyzed, combining with the composition of the QDs, which was obtained from the Raman spectra.

II. EXPERIMENTAL

The GeSi QDs sample was grown on (100)-oriented Si substrates covered by 100nm buffer layer, using a solid-source MBE system with the S-K growth mode. The sample consists of 20 period bilayers. A Ge layer and a 20-nm-thick Si spacer layer exit in each bilayer. The nominal thickness of the Ge layer is 1.5 nm. The growth temperature was 540 °C. Figure 1 shows the three-dimensional AFM images of the GeSi QDs sample. The QDs have the characteristic base size of 100 nm and the height of about 15 nm.

Figure 1 Three-dimensional AFM image of the self- assembled GeSi QDs sample at the growth temperature of 540 °C. The thickness of Ge and Si spacer layer are 1.5 and 20 nm, respectively.

PL and Raman scattering measurements were carried out in the GeSi QDs sample with an FTIR-T60 and JY T64000 system, respectively. The spectra were both

0-7803-8511-X/04/$20.00 ©2004 IEEE.
excited by the 514 nm line laser and recorded with the liquid-nitrogen-cooled CCD camera.

III. RESULTS and DISCUSSION

Figure 2 shows temperature-dependent PL spectra. The strong peak centered at around 1.1 eV is the Si transverse optical (TO) phonon assisted recombination. The peak located at higher energy than Si-TO peak arises from other recombination in Si, such as Si transverse acoustic (TA) peak and Si no-phonon (NP) peak. The broad peaks at lower energies (from 0.7 to 1.0 eV) were attributed to electron-hole recombination within the QDs or at the interface between the QDs and surrounding Si. The peaks between the Si TO-peak and the broad Ge peak arise from the Ge wetting layers.

According to equation (2) and the obtained value of the characteristic temperature \( T_B \), the relation between the confinement sizes of the QDs and the carrier effective masses in the QDs can be estimated as

\[
T_B = \frac{h^2}{2\pi^2a^2m^*_e k_B}. \tag{2}
\]

It has been found that this rule of temperature-dependence also exists in the GeSi QDs sample. The data of the temperature-dependent PL spectra in our experiments were fitted by Equation (1). And we assume that \( I(T) \) and \( I_0 \) are the integrated PL intensities at temperature \( T \) and 10K, respectively. The results of fitting are represented in figure 3, in which the dots are the experimental data and the solid line is the fitted curves. In the fitted curve, the characteristic parameters \( T_B, T_r, \) and \( \nu \) equal 31.6K, 0K, and 0.025, respectively. There is no contribution of the radiative term in this fitted curve.

\[
\frac{I(T)}{I_0} = \frac{1}{1 + \nu \cdot \exp(T/T_B + T_r/T)}, \tag{1}
\]

where \( \nu \) is characteristic reduced frequency, and \( T_B \) and \( T_r \) are characteristic temperatures. The characteristic temperature \( T_B \) is very important, which is associated with the confinement size (\( a \)) of the QDs and the carrier effective mass (\( m^*_e \)) in the QDs, and can be given by the following expression [4]

\[
m^*_e \approx \frac{1}{a^2} \cdot m^*_e, \tag{3}
\]

where the confinement size \( a \) is in nanometers unit. As mentioned above, the lateral dimensions of the presented GeSi QDs are much larger than their heights, so the confinement sizes are the heights of the QDs. The average height of the GeSi QDs sample is about 10nm by the AFM characterization. And the AFM tip effect on the size determinations has been calibrated by TEM and
excluded. Thus the carrier effective mass \( m^* \) in the GeSi QDs sample can be evaluated as about 0.014\( m_e \), where \( m_e \) is the rest electron mass. The value of this carrier effective mass is affected largely by not only the size of QDs, but also the composition of the QDs, and it is much different from those in bulk Si and Ge. In the epitaxy growth process, the atomic intermixing occurred at the Ge/Si interface. The pure Ge QDs were turned into GeSi QDs by this kind of interdiffusion. The compositions of the QDs can be estimated by the results of the Raman scattering measurements.

![Image](image.png)

**Figure 4** Raman scattering spectrum of the GeSi QDs sample.

Figure 4 shows the Raman scattering spectrum of the GeSi QDs sample. In the spectrum, two obvious peaks were observed besides the strong Si substrate signal around 520 cm\(^{-1} \), which were Ge-Ge optical phonon mode around 300 cm\(^{-1} \) and Si-Ge mode around 410 cm\(^{-1} \). The Ge-Ge optical mode mainly arises from the Ge dots rather than the Ge wetting layers. Si-Ge mode implies the formation of SiGe alloy in the sample. The composition of the QDs can be determined by the integrated peak intensity ratio \( I_{\text{Ge-Ge}}/I_{\text{Si-Ge}} \), which can be expressed as [6]

\[
\frac{I_{\text{Ge-Ge}}}{I_{\text{Si-Ge}}} \approx \frac{1.6x}{1-x},
\]

where \( x \) is the Ge composition of QDs. The result of the evaluation is that the Ge composition of the QDs is about 50%.

**IV. CONCLUSION**

In conclusion, a novel approach has been proposed to evaluate the carrier effective mass in QDs structures by PL and Raman scattering measurements. The carrier effective mass in the self-assembled GeSi QDs sample has been extracted from the temperature-dependence of the PL fitted by the combination of Arrhenius and Berthelot type functions. The composition of the GeSi QDs was estimated from the Raman spectrum.

**Acknowledgments**

The work in NJU was supported by the National Natural Science Foundation of China under Grant Nos. 90101021 and 60290084. The work in UCR was supported by DARPA through the Center for Nanoscale Innovation for Defense.

**References**