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Experimental investigation of Hall mobility in Ge/Si quantum dot superlattices

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We report results of measurements of Hall mobility in a set of doped and undoped Ge_xSi_{1-x}/Si quantum dot superlattices ($x=0.50$ and 0.73). The dome-shaped Ge quantum dots have the characteristic base size of 40 nm and height of about 4 nm. The molecular beam epitaxy grown structures consist of 5–20 layers of Ge quantum dots separated by 20-nm-thick Si layers. The position of δ doping varies for different samples. The average measured in-plane Hall mobility for p-type structures is 140 $cm^2\,V^{-1}\,s^{-1}$ at 300 K and 2.4×10^3 $cm^2\,V^{-1}\,s^{-1}$ at 77 K. Relatively large values and temperature dependence suggest that in given quantum dot structures the carrier transport is likely of the band conduction type rather than hopping type. These results are important for proposed optoelectronic and thermoelectric application of quantum dot superlattices. *© 2004 American Institute of Physics.* [DOI: 10.1063/1.1713049]

Quantum dots and different types of quantum dot arrays continue to attract significant attention of the physics and device research communities.[1] Quantum dot superlattices (QDS) have been recently proposed for photodetectors, photovoltaics, and thermoelectric applications.[1–5] In all of the envisioned applications it is crucial to maintain relatively high carrier mobility or product of the mobility and carrier concentration. The photogenerated carriers in quantum dot photodetectors or photovoltaic cells should be able to travel to the metal contact before they recombine. Good carrier mobility and electric conductivity are also important for thermoelectric materials where the figure of merit Z at given temperature T is defined as $ZT=\alpha^2\sigma T/K$ (α is Seebeck coefficient, σ is electrical conductivity, and K is thermal conductivity). Carrier transport in quantum dot arrays can manifest both hopping transport and conduction band transport features.[6] The hopping transport regime is characterized by much lower mobility values than the band conduction transport, and by different temperature dependence. What transport regime would prevail depends on the structural and morphological properties of QDS. Despite its importance for practical applications there has been little work done on carrier transport in QDS.[7]

In this letter we report results of measurements of Hall mobility in a set of Ge_xSi_{1-x}/Si QDS grown by molecular beam epitaxy (MBE).[8–10] For this study we have used two batches of QDS samples (both doped and undoped) fabricated by two different research groups. The undoped samples JL264 and JL265 with typical Ge content in the dots of 50% have been grown in a Perkin Elmer MBE system. The doped samples LJ017, LJ018, and LJ021 with Si content in the dots less than 27% have been grown in a Riber EVA32 at UCLA. All investigated QDS with either five or twenty layers of quantum dots have been grown on p-type Si wafers [see Fig. 1(a)]. There are three different positions for δ-doping layer in the doped QDS [Figs. 1(b)–1(d)]. Although Hall mobility μ_H cannot be easily translated to the electron (hole) drift mobility $\mu_e(\mu_h)$, unless the sample has only one type of carriers, it represents a measure of the overall mobility of both electrons and holes in given sample.

The Ge/Si QDS samples used in this study were fabricated using a solid-source MBE system. p-type (100) Si with a resistivity of 8–10 Ω cm was used as a substrate and cleaned using a standard Shiraki clearing method followed by *in situ* thermal cleaning at 930 °C for 15 min. The substrate temperature has been maintained at 550 °C during the

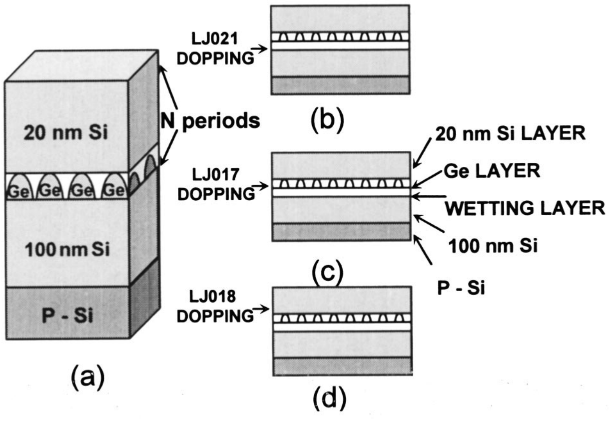

FIG. 1. Schematic of sample structure (a), and location of the δ doping (b).

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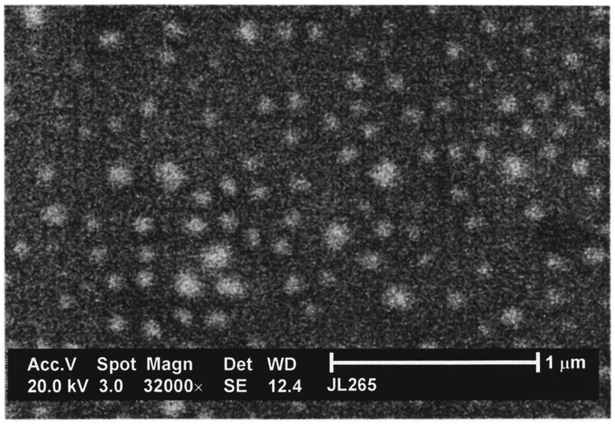

FIG. 2. Scanning electron microscopy (SEM) image of Ge quantum dots on Si grown by molecular beam epitaxy.

epitaxial growth. The nominal growth rates were 1 and 0.05 Å/s for Si and Ge, respectively. Four types of samples have been grown. The first type is undoped and the other three types are boron δ-doped in wetting layer, 6 Å Ge dots layer, and Si cap layer, respectively [see Figs. 1(b)–1(d)]. Boron doping is achieved by sublimation of boron from a Knudsen cell. The samples consist of a 100 nm undoped Si buffer layer, five or twenty periods of Ge quantum dots separated by 20-nm-thick Si spacer layer and 50-nm-thick cap layer on the top [Fig. 1(a)]. The doping density in the Si capping layer was about 5×10^{18} cm^{-3}.

Figure 2 shows a scanning electron microscopy (SEM) image of the top layer of the undoped Ge/Si quantum dot samples. The Ge dots can be seen as bright disks. From this SEM image, we can determine some characteristics of the quantum dot array. We estimated that the density of Ge quantum dots is about 3×10^9 cm^{-2} and the average base diameter is 40 nm. The height of 4 nm has been determined from the atomic force microscopy scans. From the data obtained by micro-Raman spectroscopy we have established that the Ge dot layers were not under very strong strain. This conclusion is based on comparison of Si and Ge peak positions in Ge/Si QDS with those in bulk Si ($520.4\,\mathrm{cm}^{-1}$) and Ge ($301\ \mathrm{cm}^{-1}$). Raman spectroscopy has been carried out using Renishaw instrument under 488 nm laser excitation. In some QDS samples, the peak position coincides almost exactly with bulk. The spectra of undoped samples LJ017 and LJ018 exhibited only small deviation ($\sim$1 cm^{-1}).

Thermally diffused contacts made of aluminum were formed on top of the superlattices to carry out Hall measurements. Extended annealing time has been chosen to make sure that the contact is formed for all layers of quantum dots. The voltage was applied across the gap between the pairs of two electrodes, so that current flows parallel to the quantum dot layers. The Hall mobility was measured using EGK HEM-2000 system at the room temperature and 77 K. The measurements were conducted in a standard four-terminal scheme to ensure the accuracy. The data points were taken at the magnetic field of 0.37 T. Before measuring mobility in QDS we have tested the setup and experimental procedure on several reference samples consisted of conventional Si/Ge quantum well superlattices.

Figure 3 presents Hall mobility in p-type doped Ge/Si quantum dot superlattices at 77 K. The Hall mobility μ_H is shown as a function of input current I_{inp} to demonstrate its weak dependence on I_{inp}. The Hall mobility μ_H is defined as the product of the Hall coefficient R_H and the electric conductivity σ:

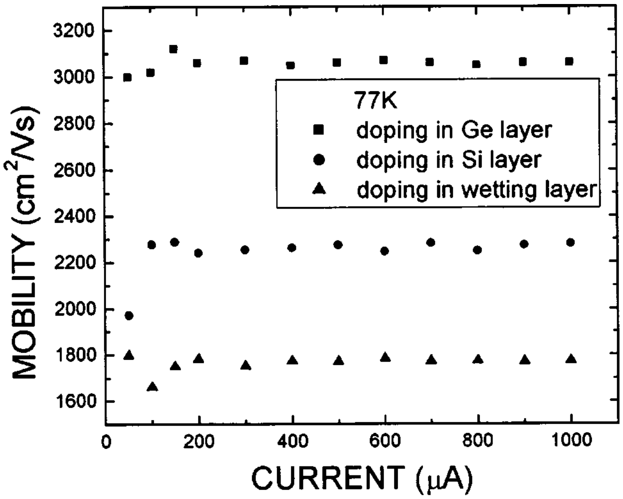

FIG. 3. Hall mobility μ_H in the doped Ge/Si quantum dot superlattice at 77 K.

$$\mu_H=|R_H\sigma|, \tag{1}$$

where $R_H=(p-nb^2)/e(p+nb)^2$, and $b=\mu_e/\mu_h$ is the ratio of the electron μ_e and hole μ_h drift mobilities, n (p) is the electron (hole) density, and e is the charge of an electron. The measured values of the Hall coefficient were positive indicating the overall p-type conduction. Table I summarizes the average measured values of the Hall mobility for the undoped and doped quantum dot superlattices.

For comparison, the room temperature electron (hole) drift mobility in bulk Si and Ge are $\mu_e=1500$ cm^2 V^{-1} s^{-1} ($\mu_p=450$ cm^2 V^{-1} s^{-1}) and $\mu_e=3900$ cm^2 V^{-1} s^{-1} ($\mu_p=1900$ cm^2 V^{-1} s^{-1}), respectively. Electron (hole) drift mobility at 77 K can be estimated from the expression

$$\mu=\mu_0\left(\frac{T}{T_0}\right)^{-3/2}, \tag{2}$$

where $T_0=300$ K and μ_0 is the drift mobility at $T=300$ K.[12] Thus, at 77 K one gets $\mu_e=3.0\times10^4$ cm^2 V^{-1} s^{-1}, μ_p

TABLE I. Hall mobility in Ge/Si quantum dots superlattices.

	300 K		77 K	
Quantum dot superlattices	μ_H (cm^2/Vs)	N_b (cm^{-3})	μ_H (cm^2/Vs)	N_b (cm^{-3})
JL264 undoped $N=5$	239	7.57×10^{18}	7.2×10^3	2.86×10^{18}
JL265 undoped $N=20$	228	1.76×10^{18}	6.4×10^3	7.98×10^{17}
LJ017 doping in Ge layer $N=5$	149	3.13×10^{19}	3.1×10^3	8.37×10^{18}
LJ018 doping in Si layer $N=5$	143	2.89×10^{19}	2.2×10^3	6.10×10^{18}
LJ021 doping in wetting layer $N=5$	129	3.79×10^{19}	1.8×10^3	6.51×10^{18}

$=1.5\times10^4$ cm^2 V^{-1} s^{-1} for intrinsic Si, and $\mu_e=1.2\times10^4$ cm^2 V^{-1} s^{-1}, $\mu_p=3.5\times10^3$ cm^2 V^{-1} s^{-1} for intrinsic Ge.

As one can see from Table I, the average measured Hall mobility for the doped Ge/Si quantum dot superlattices is about 140 cm^2 V^{-1} s^{-1} in room temperature and 2.4×10^3 cm^2 V^{-1} s^{-1} at 77 K (averaged for three types of samples). The average value for the undoped QDS is 233.5 cm^2 V^{-1} s^{-1} at room temperature, and 6.80×10^3 cm^2 V^{-1} s^{-1} at 77 K. These values are much less than those for Si and Ge Hall mobilities. Another observation is that the Hall mobility in QDS does not strongly depend on the location of δ doping. The measured Hall mobilities are about a factor of two less than the drift hole mobility in intrinsic Ge. At the same time the QDS Hall mobility values are larger than typical mobility values in the hopping conduction regime. The decrease of the Hall mobility in QDS compared to the bulk intrinsic value can be attributed to the presence of the potential barriers at the Ge/Si interface, charging effects, surface disorder, dislocation, and alloy scattering, etc. Moreover, most of the band discontinuity between Ge and Si resides in the valence band thus stronger impeding the hole transport. The apparent Hall carrier concentration is larger in the doped QDS samples than that in the undoped QDS samples. The Hall mobility in the doped QDS is lower, which might be attributed to the presence of additional carrier relaxation mechanisms in these samples such as scattering on dopant atoms. A study of the dislocation line density conducted for the samples grown by the same group[13] indicates that the high-density dislocations are generated when the number of layers is larger than 25. Thus, in the investigated QDS samples the role of the dislocation lines on the carrier transport is not expected to be dominant. The fact that the mobility is the lowest in the samples with δ doping in the wetting layer suggests that they do contribute to the transport.

As seen from Table I, the Hall mobility at 300 K is much smaller than that at 77 K, which is characteristic for the band conduction-type transport. Indeed, in conventional semiconductors, mobility increases with decreasing temperature (from 300 to 77 K) due to reduction in phonon scattering.[11,12] In the hopping transport regime, characteristic for disordered systems, the temperature dependence of the mobility is different. This regime is sometimes observed in quantum dot arrays[6,14] or nanoparticle samples. Under the assumption of conventional phonon-assisted hopping transport regime the conductance in quantum dot array is described by the equation[14] $G(T)=G_o\exp[-(T/T_o)^x]$, where T_o is a parameter determined by the properties of the material, and parameter $x<1$ is defined by the energy dependence of the density of states near the Fermi level. When the interaction energy between electron and hole is large compared to energy perturbation due to disorder, parameter $x=1/2$, and the conductivity is described by the Efros–Shklovskii law.[15] In the hopping transport regime, the mobility is higher and, correspondingly, the resistivity is lower at high temperature than at low temperature due to the temperature activation mechanism. Results of our measurements suggest that for given Ge/Si quantum dot superlattices the carrier transport is of the band type rather than thermally activated hopping type.[14–16] At the same time, the final conclusions about the transport mechanisms in QDS can be made only after accumulation of sufficiently more experimental data. In the case of high electric field, the variable range hopping can also be electric field-assisted. For comparison, the low temperature (4.2 K) mobility value in conventional Si/Ge quantum well superlattices is about 1.4×10^4 cm^2/(V s).[17] Hole mobility in strained Si$_{1-x}$Ge$_x$ alloys for $0.17<x<0.29$ as reported in Ref. 18 is in the range from 49.8 to 30.3 cm^2/(V s) (at doping concentrations from 2×10^{18} to 7.5×10^{18} cm^{-3}), which is noticeably smaller than in QDS investigated in the present work.

In conclusion, we measured Hall mobility in a set of doped and undoped Ge$_x$Si$_{1-x}$/Si quantum dot superlattices. The average in-plane Hall mobility for p-type structures was determined to be 140 cm^2 V^{-1} s^{-1} at room temperature and 2.4×10^3 cm^2 V^{-1} s^{-1} at 77 K. The Hall mobility only weakly depended on the location of δ doping. Relatively large mobility values and its temperature dependence suggest that the carrier transport is of the band conduction type[19] rather than hopping conductivity type in these quantum dot superlattices.

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