Intraband absorption in Ge/Si self-assembled quantum dots

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(Received 25 September 1998; accepted for publication 9 November 1998)

We have observed intraband absorption in Ge/Si self-assembled quantum dots. The self-assembled quantum dots are grown at 550 °C by chemical vapor deposition. Atomic force microscopy shows that the quantum dots have a square-based pyramidal shape (≈100 nm base length) and a density $\approx 2\times 10^{9}\,\mathrm{cm}^{-2}$. Intraband absorption in the valence band is observed around 300 meV (4.2 μm wavelength) using a photoinduced spectroscopy technique. The intraband absorption is in-plane polarized. It is attributed to bound-to-continuum transitions since the intraband energy corresponds to the energy difference between the Si band gap and the photoluminescence energy of the quantum dots. The magnitude of the intraband absorption saturates when the ground level of the quantum dots is filled. This feature allows the measurement of the in-plane absorption cross section of the intraband transition which is found as large as $2\times 10^{-13}\,\mathrm{cm}^{2}$. © *1999 American Institute of Physics.* [S0003-6951(99)01403-5]

The existence of intersubband transitions in semiconductor quantum wells has led to the development of a new class of infrared photodetectors, the quantum well infrared photodetectors (QWIPs). Most of the developments in QWIPs including the realization of mid-infrared focal plane arrays have been realized using the intersubband transitions in the conduction band of GaAs quantum wells.[1] Few attempts have been made to realize QWIPs using the intersubband transitions in the valence band of $Si_{1-x}Ge_x/Si$ quantum wells.[2,3] The use of Si/SiGe heterostructures presents the advantage to be compatible with silicon-based complementary metal–oxide–semiconductor (CMOS) signal processing.

Recently, it has been shown that self-assembled InAs/GaAs quantum dots can exhibit intraband absorption in the mid-infrared spectral range.[4,5] The use of self-assembled semiconductor quantum dots instead of quantum wells for infrared photodetection has been consequently proposed. First, demonstrations of quantum dot infrared photodetectors have been reported in the literature using III–V In(Ga)As/GaAs quantum dots.[6,7]

Self-assembled quantum dots can also be grown on silicon due to the 4% lattice mismatch between Ge and Si. Numerous studies have reported on the formation of nanometer size Ge quantum dots deposited on Si using different growth techniques.[8–11] The Ge/Si quantum dots which exhibit a large band discontinuity in the valence band could also be appropriate for infrared photodetection like the InAs/GaAs quantum dots. It appears that Ge/Si quantum dots could combine the advantages of quantum dots as compared to quantum wells while keeping the compatibility with Si-based signal processing.

In this letter, we show that Ge/Si self-assembled quantum dots exhibit intraband absorption in the mid-infrared spectral range. The intraband absorption is in-plane polarized and corresponds to transitions from the ground state of the dots to the continuum states. To our knowledge, such a transition has not yet been reported in Ge dots. The observation of intraband absorption associated with Ge dots opens the route to the realization of Si-based quantum dot infrared photodetectors.

The investigated samples were grown by ultrahigh-vacuum chemical vapor deposition (UHV-CVD) using silane and germane as gas precursors. The deposition of Ge was accurately monitored *in situ* by reflection high-energy electron diffraction (RHEED).[11] Structural characterizations of the Ge dots were performed by atomic force microscopy (AFM Scientific Park Instruments). The samples were also characterized by standard low-temperature photoluminescence. For mid-infrared absorption measurements, ten layers of Ge separated by 22 nm thick Si barriers were grown at 550 °C. The last Ge layer was not covered with Si for AFM measurements. The sample was thereafter polished with 45° facets in a multipass waveguide geometry.[4] The infrared absorption was measured using a photoinduced spectroscopy technique.[12] Carriers are generated in the quantum dots using a mechanically chopped interband optical pumping (Ar^{+} ion laser). The absorption is measured as the normalized variation of transmission of an infrared beam delivered by a Fourier transform infrared spectrometer.

In Ref. 11, the formation of precursor clusters by UHV-CVD has been evidenced for the deposition of a single Ge layer. These precursor clusters appear before the onset of the two-dimensional (2D) to 3D growth mode transition, as observed by RHEED. They consist of truncated square-base pyramids with {105} facets. The typical sizes of the precursors are 50 nm base width and 2 nm height. Their density is small, around $6\times 10^{7}\,\mathrm{cm}^{-2}$. The quantum dot *multilayer* samples investigated in this work were grown in similar conditions than for the formation of the precursor clusters.[11] However, the multilayer stacking modifies the size, the shape and the density of the precursors. Figure 1 shows an AFM image of the surface of the ten layers Ge/Si quantum dot sample. The surface exhibits square-based pyramidal Ge dots which are oriented along [100] and [010] directions like for the precursors. However, the dot density is $\approx 2\times 10^{9}\,\mathrm{cm}^{-2}$. The average size of the dot base length is around 100 nm, the

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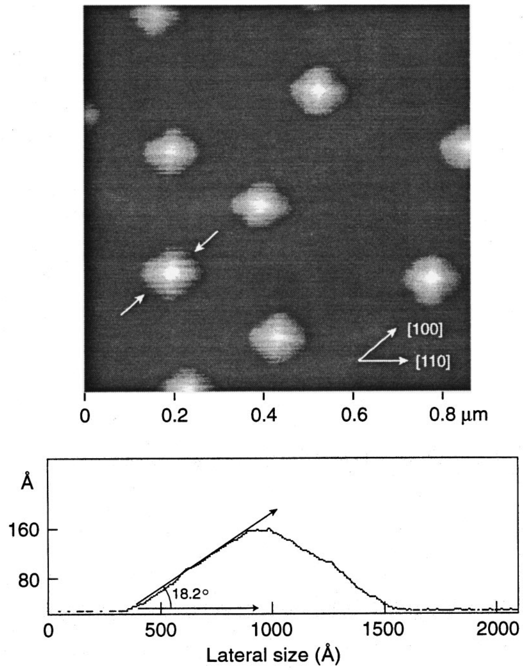

FIG. 1. AFM topographical image of the Ge/Si self-assembled quantum dots. The image shows the shape and size of the quantum dots at the top of a ten multilayer sample (top). The quantum dots are pyramidal with a square-base oriented along [100] and [010] directions. The AFM cross-sectional height profile of one dot is shown (bottom).

height is ≈16–17 nm, and the dot uniformity is better than ±10%, as estimated by the histogram of island size distributions given by AFM. The four sidewall facets are formed by {103} and {104} planes, but dominated by {103} planes (the measured mean inclination angles are ≈18° and 14°).

Figure 2 shows the photoluminescence at 77 K of the ten layer sample. At this temperature, the photoluminescence of the wetting layer is not observed and the photoluminescence spectrum is dominated by the radiative recombination associated with the Ge dots. The photoluminescence is maximum at 845 meV with a full width at half maximum of 70 meV. The photoluminescence of the ten layer sample is redshifted as compared to the photoluminescence of the precursor clusters.[11] It is important to note that the radiative recombination in Ge/Si quantum dots is of type II. The recombination occurs between the electrons in the Si layers and the holes confined in the Ge dots. This situation is depicted in the inset of Fig. 2. Note that the energy diagram in Fig. 2 shows that the energy difference between the ground state of

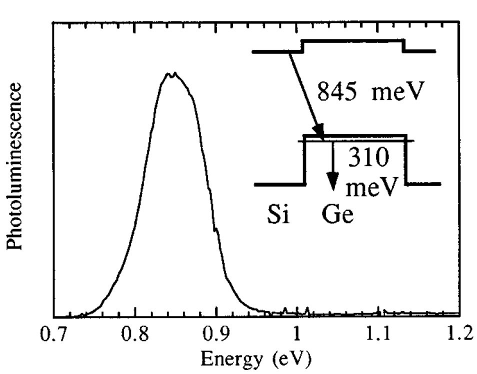

FIG. 2. 77 K photoluminescence of the Ge/Si self-assembled quantum dots. The inset shows a schematic energy band diagram (not to scale).

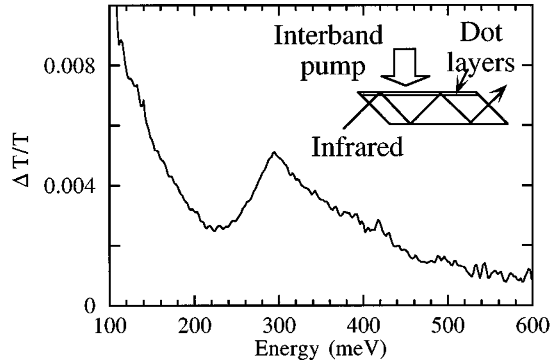

FIG. 3. Normalized variation of transmission $\Delta T/T$ for the Ge/Si self-assembled quantum dots under optical pumping. The interband pump intensity is 10 W cm^{-2}. The measurement is performed at 77 K. The inset shows schematically the experimental setup.

the quantum dots and the silicon barrier is around 300 meV.

The photoinduced infrared absorption spectrum of the Ge/Si self-assembled quantum dots is reported in Fig. 3. The measurement is performed at 77 K with unpolarized infrared light. The photoinduced absorption is dominated by an asymmetric absorption line with a maximum around 300 meV. This absorption is attributed to the intraband absorption in the valence band of the Ge/Si quantum dots. The free-carrier absorption associated with the carriers which are not trapped in the dots can also be observed as a monotonously increasing absorption towards low energy.[13] The polarization selection rule of the intraband absorption has been checked. The intraband absorption amplitude in *p* polarization (half of the electric field along the growth axis, half of the electric field in the layer plane) is divided by a factor of 2 as compared to the absorption amplitude in *s* polarization (electric field in the layer plane). The intraband absorption is therefore in-plane polarized. The energy at maximum of the absorption (295 meV) matches very nicely the experimental energy difference between the silicon band gap and the photoluminescence energy of the quantum dots. We attribute therefore the infrared absorption to an intraband transition between the dot ground states to the continuum states. The large broadening and asymmetric line shape are also characteristic of a bound-to-continuum transition. Note that a similar bound-to-continuum transition has also been observed in the valence band of InAs/GaAs self-assembled quantum dots.[5] The intraband absorption was also in-plane polarized like for Ge dots. We underline that the bound-to-continuum nature of the intraband absorption reported here for Ge/Si self-assembled quantum dots is particularly appropriate for normal incidence infrared photodetection.

The absorption amplitude of the intraband absorption as a function of the pump excitation density is reported in Fig. 4. At low intensity, the absorption increases as the number of photocreated carriers increases. Above 10 W cm^{-2}, the photoinduced absorption saturates. This saturation is due to the filling of the dot ground states. As the dot density is 2×10^9 cm^{-2}, the complete filling of the dot ground state corresponds to a 4×10^9 cm^{-2} carrier density (2 holes per dot). This injected carrier density at saturation can also be estimated from rate equations. The carrier density is given by $n=G\tau$, where $G=\alpha I/h\nu$ is the generation rate, α the absorption probability, I the pump intensity, $h\nu$ the photon en-

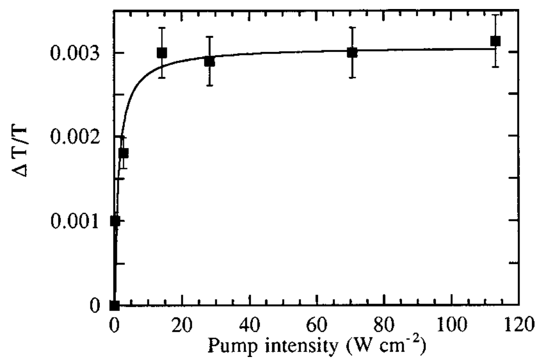

FIG. 4. Amplitude of the infrared photoinduced absorption in the Ge/Si self-assembled quantum dots as a function of the interband pump density. The measurement is performed at 77 K. The full line is a guide to the eye.

ergy, and τ the interband recombination lifetime. Assuming $\alpha = 2.5\times 10^{-4}$,[14] $I = 10\,\mathrm{W\,cm^{-2}}$ at 514 nm, and $\tau \sim 1\,\mu$s, the estimated injected carrier density is $n \sim 6\times 10^{9}\,\mathrm{cm^{-2}}$ which agrees with the assumption of the filling of the quantum dot ground states. The discrepancy between the two estimations stems from the uncertainty on the interband recombination time. The in-plane absorption cross section σ of the intraband absorption can be deduced from the following equation:

$$\frac{\Delta T}{T} = N_p \sigma n \frac{S_{\mathrm{pump}}}{S_{\mathrm{infrared}}}, \tag{1}$$

where N_p is the number of quantum dot layer planes, n the areal carrier density, and S_{pump} and S_{infrared} the surfaces of the interband pump and infrared probe. At saturation, the carrier density is given by the dot density. Assuming an experimental ratio $S_{\mathrm{pump}}/S_{\mathrm{infrared}} = 0.4$ and that nine layer planes are involved in the absorption, we find an intraband absorption cross section $\sigma = 2\times 10^{-13}\,\mathrm{cm^2}$. This giant value is about three orders of magnitude larger than the absorption cross section measured for the bound-to-continuum intraband transition in the valence band of InAs/GaAs quantum dots ($3\times 10^{-16}\,\mathrm{cm^2}$).[5] It demonstrates that apart from the advantage of in-plane intraband absorption (i.e., normal incidence absorption), Ge/Si self-assembled quantum dots appear very promising for infrared photodetection.

A crucial point in Ge/Si self-assembled quantum dots is related to the confinement energy in the valence band. The valence band offset for pure Ge on Si is around 700 meV. The observation of photoluminescence at 845 meV should require approximately a 400 meV confinement energy for the ground state in pure Ge dots. This large confinement energy is not compatible with the relatively large dot size observed by AFM. Several features can, however, explain the high energy of the photoluminescence. The size of the Ge clusters can be significantly reduced after Si overgrowth. The Ge dots and the Si barriers can be intermixed, leading to an average $Si_{1-x}Ge_x$ composition in the quantum dots. Strain variation and relaxation inside the dot can also occur, leading to a reduced confinement potential volume as compared to the physical size observed by AFM. All these features indicate that the confinement energy is not necessarily negligible in the Ge/Si clusters, and at least much larger than the confinement energy of a pyramid with a 100 nm thick base length and a 17 nm height. The infrared measurements presented in this work reinforce this hypothesis. The saturation of the absorption due to the filling of the ground states is clearly observed like in the case of InAs/GaAs quantum dots,[5] thus indicating that there is not a quasicontinuum density of states available. The resonant shape of the bound-to-continuum intraband absorption is very similar to the one observed in quantum wells or quantum dots. This feature also indicates that the Ge/Si self-assembled clusters are not equivalent to heterojunctions like those used for internal photoemission sensors.[15]

In conclusion, we have shown that Ge/Si self-assembled quantum dots exhibit intraband absorption in the mid-infrared spectral range (4 μm wavelength). The intraband absorption is in-plane polarized with a very large absorption cross section. These results open the route to the realization of Ge/Si quantum dot infrared photodetectors.

The authors would like to thank E. Finkman and J.-M. Lourtioz for fruitful discussions. This work was partly supported by France Telecom-CNET under convention 981B044.

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