Luminescence of laterally ordered Ge islands along ⟨100⟩ directions

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The optical properties of coherently strained, self-ordered Ge islands are analyzed in connection with their size distribution. The ordering was achieved by depositing Ge on Si mesas oriented parallel to ⟨100⟩ directions and grown by selective epitaxy on Si(001) using low pressure chemical vapor deposition. The spontaneous ordered nucleation of Ge islands along mesa edges is driven by the presence of tensile strain at the periphery of the mesas. All photoluminescence peaks of the islands as well as of the wetting layer are well resolved. The emission peaks of ordered islands could be separated from the emission of randomly distributed islands on the (001) plane by varying the width of the straight mesa lines. The peaks of ordered islands are narrower than from random islands in agreement with the atomic force microscopy analysis. This effect is due to the strong island–island interaction in the one-dimensional row. The emission is governed at low temperature by hole transfer from the wetting layer to the islands, and at higher temperature by hole transfer from the islands to the wetting layer. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1481205]

I. INTRODUCTION

The self-ordering of islands on mesas during epitaxial deposition is very promising for the realization of large densities of islands with good homogeneity. Mesas with certain edge orientations can be realized by lithography and reactive ion etching. Another approach is the selective epitaxial growth (SEG) on patterned wafers. Strain field distribution on Si mesas grown by SEG was determined by Jin *et al.* by micro-Raman spectroscopy.[1] The results suggested a tensile strain near the periphery of the mesa and a compressive strain at the center. Jin *et al.* concluded that the strain distribution of Si mesas is the driving force for the preferential nucleation of Ge dots along mesa edges.[2–4] Ge nucleates in ordered, single or multiple rows.[2,4–6] The ordering occurs along edges parallel to ⟨110⟩ directions,[5,7] but also along ⟨100⟩ directions.[2,4,6] Even single Ge dots could be grown in small windows of the dimension of an island.[7] For mesas parallel to ⟨100⟩ directions the ordering occurs on high index planes (such as {12 1 0}), near the edge to the {110} plane (which always forms).[8] A second dense row of islands also forms on the {110} facets. By varying the coverage a value of 100 μm for the diffusion length of Ge adatoms was evaluated at 700 °C.[6] The linear density of islands is almost independent on the size of the patterns, but the volume of islands decreases due to a decrease of the coverage on the mesa as the mesa size reduces.

Here, we analyze the photoluminescence (PL) of ordered islands for a coverage of ~5 eq-ML Ge deposited at 700 °C on Si mesas grown by SEG on patterned Si(001) wafers. The patterns were oriented along ⟨100⟩ directions. We observe well resolved and intense PL from ordered islands and discuss in detail the peculiarities of light emission from random and ordered islands.

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II. EXPERIMENTAL DETAILS

Growth was performed on 20 Ω cm *n*-type nontilted Si(001) substrates (usually 0.5° off) with thermal oxide patterned by optical lithography followed by reactive ion etching. The pattern consisted of periodic arrays of 4 mm long rectangular windows parallel to ⟨100⟩ directions and with variable width (1.6–300 μm). Each dimension covered an area of 4×4 mm^2. Before epitaxy the wafers are cleaned by standard RCA cleaning. Epitaxial growth was carried out in a cold wall, load-locked, high-vacuum low pressure chemical vapor deposition system with a base pressure of 7×10^{-8} Torr.[9] Source gases were $SiCl_2H_2$ and GeH_4 and carrier gas was H_2. First, the protective thin oxide was removed by heating under H_2 at 950 °C at a total pressure of 1 Torr for 10 min. The growth conditions of Si mesa stripes were chosen such that the $\{h10\}$ facets were formed. To achieve this, Si was deposited at 800 °C. The {12 1 0} facets that form at 800 °C extend faster than steeper facets, because they are quite shallow (4.76°). Therefore, stripes with only facets can be realized easily by conventional lithography. Growth rate of Si was 8 nm/min. Subsequently, Ge was deposited at 700 °C with a growth rate $R_{Ge}(001)$ ~0.04 eq-ML/s. Both Si and Ge grow selectively between substrate and oxide mask.[10] The samples investigated are described in Table I. The thickness was determined by Rutherford backscattering spectrometry (RBS). The capped samples were grown for PL studies, while the uncapped samples for evaluation of the width of facets or to study the ordering. Since *time* is a parameter that plays an important role in the kinetics of islands, both types of samples were annealed for 1 min after deposition of Ge. The islands were studied with a Digital Instruments Nanoscope IIIa atomic force microscope (AFM) in tapping mode. The PL was measured using a Fourier transform spectrometer (BIO RAD FTS40) equipped with a cooled Ge detector and an argon ion laser emitting 50 mW at 488 nm wavelength.

TABLE I. Data of samples for investigations by AFM (Si buffer–Ge) and by PL (Si buffer–Ge–Si cap); $T_{epi}(Ge)=700\,^{\circ}C$, $R_{Ge}(001)=0.04$ eq-ML/s, flow $(GeH_4)=0.1$ sccm, flow $(H_2)=200$ sccm, $p_{tot}=0.1$ Torr.

Sample No.	Substrate $\{hkl\}$	Buffer thickness (nm)	Ge deposition (time) (s)	Ge coverage (nm)	Si cap (nm)	Stripes without (001) plane (μm)
1594	001	515	114	0.79	87	<4
1731	001	515	114	0.70	0	<4
1602	001	775	114	0.67	72	<11
1604	001	980	114	0.80	100	<11
1648	001	980	60	0.50	90	<11
1641	001	170	120	0.79	0	
1641	011	78	120	0.22	0	
				$\pm 10\%$		

The growth rate of Si on $\{h10\}$ facets is known from earlier studies,[11] however to see if the growth rate on large wafers is the same as on facets, depositions on unpatterned (011) substrates were also performed. Table I shows for No.1641 a thickness of 170 nm on (001) wafers, while on (011) wafers the thickness is only 78 nm, corresponding to a relative growth rate on the (011) surface of 0.46. This value is near the value of $R_{\{110\}}/R_{\{001\}}=0.50$ found for growth on {110} facets at 700 °C and $R_{\{110\}}/R_{\{001\}}=0.44$ at 750 °C reported earlier in Ref. 11. The fact that the relative growth rates on unpatterned wafers and on facets are approximately the same implies that growth of Si from $SiCl_2H_2$ in the temperature range 700°–800 °C and total pressure of 0.1 Torr is determined by the incorporation rate (dependent on crystal orientation) and not by temperature dependent surface phenomena such as surface diffusion of Si adatoms.

III. ISLAND MORPHOLOGY

The growth conditions were chosen so as to alllow on a large area the formation of a bimodal distribution of islands. The island density on unpatterned Si(001) was ~ 0.6 domes/μm^2 and ~ 1.9 pyramids/μm^2. One purpose of the investigation was to see if the ordering has an influence on the size distribution.

On mesas, the nucleation is randomly on the (001) part and ordered along the edges.[2–4] In the present work the mesas have {12 1 0} and {110} facets. Ge islands order on the {12 1 0} facets in single dense rows, near the edge to the {110} facets.[6] While *the facet width is the same* on all stripes of a given buffer thickness, the contribution of facets to the total area increases with decreasing width, since their total length increases while the contribution of the (001) plane decreases. The facet width depends on the buffer thickness. It is ~ 1.6 μm for the thin buffers (~ 500 nm) and ~ 3.2 μm for the thicker buffers (~ 1000 nm).

Figure 1(a) represents a three-dimensional (3D) AFM scan of 1.7 μm mesa stripes and Fig. 1(b) shows two scans of ordered islands. The linear density of ordered islands does not change significantly with stripe width. It is 5.5 ± 0.5 μm^{-1} [see Fig. 2(a)]. However, AFM scans of ordered

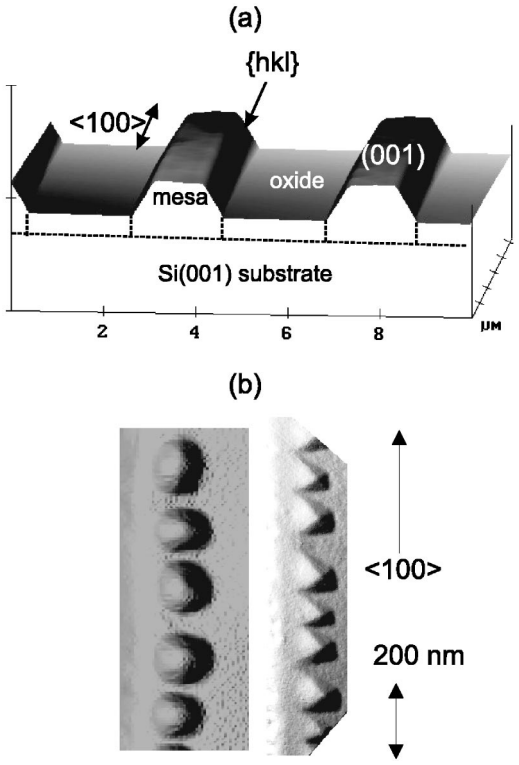

FIG. 1. (a) 3D-AFM image of Si mesa stripes oriented along ⟨100⟩ directions and (b) 2D-AFM images of islands nucleated along the mesa edges on a large mesa (left) and on a narrow mesa (right).

islands show that on stripes of width 300–30 μm the islands are quite ''balled up,'' having an aspect ratio (height/width) of ~ 0.19 [see Fig. 2(b)]. But for narrower mesas the islands evolve toward flatter shapes, their aspect ratio decreasing to 0.04. While the linear density of islands remains constant within 10%, the island height decreases from 34 to 6 nm on the narrowest stripe of uncapped islands. This must be due to a decrease of the total amount of Ge deposited on a mesa, which is due to the lower growth rate R_{Ge} on facets. In Table I sample No.1641 has a Ge thickness on Si(011) for large area deposition of 0.22 nm, while on Si(001) it is 0.79, leading to a growth rate ratio for Ge of 0.28. The effect of lower growth rate of Ge on $\{h10\}$ planes becomes obvious for stripes with only facets, i.e., $\leqslant 4$ μm [Fig. 2(b)]. This result has implications for the PL, as shown further in Sec. IV D.

The strain distribution on the Si mesa surface results in gradients in the chemical potential that significantly influence surface diffusion of the adatoms.[12] The surface strain energy is an important component of the chemical potential along the surface. A nonuniform chemical potential produces surface diffusion fluxes proportional to the chemical potential gradient. Adatoms will tend to move to regions of low strain (low chemical potential) enhancing collection and sustained growth in these regions. There are two competing processes that define the typical time scale: deposition and diffusion. At a given temperature, growth rate, and growth time the surface diffusion can be influenced by varying the lateral scale available for diffusion. If we assume, as demonstrated by Jin *et al.*,[1] that mesa edges are tensile strained, then ordered tensile strained sites must be available, having a lower

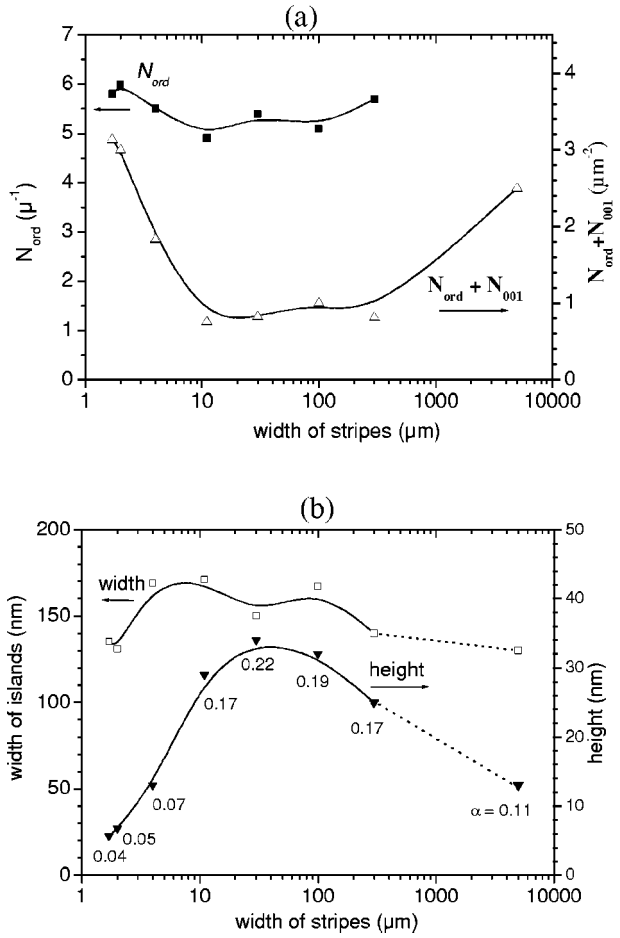

FIG. 2. Island size in function of stripe width measured by AFM: (a) linear density of ordered islands and areal density of ordered plus random islands; (b) width and height of ordered islands; the point at 5000 μm corresponds to the unpatterned area. α is the aspect ratio (height/width).

nucleation barrier than the sites on the (001) plane. Moreover, if the edges are within the diffusion length of Ge adatoms, Ge will nucleate there. The nucleation of a single row reflects the existence of a line along which the strain is minimum, ensuring the ordering along a straight line.

It is interesting to note that ordered islands have a *monomodal* distribution on all stripes [see Fig. 1(b)]. While on the (001) part of the mesas the ripening is not accomplished and pyramids are still present, on the facets the ripening is expected to be faster, since it is the consequence of the exchange of adatoms mainly between the neighbors in the row. This leads to a better uniformity of island size in the row, since the interisland distance is much smaller than between islands on the (001) part. A monomodal distribution also occurs for islands ordered along $\langle 110 \rangle$ directions.[1]

The *equidistance* is the result of the island–island interaction and of the perfection of the facets. If the repulsion were below a certain value, we would expect islands to form without spacing, or even a straight wire would form, which was indeed observed for $Si_{0.70}Ge_{0.30}/Si(001)$.[10] For pure Ge deposition the distortion of the substrate is high,[13] leading to a significant island–island repulsion through the substrate. The competition between a lower energy barrier for nucleation on the edges and the repulsive forces between the ordered islands through the substrates, results in an interisland distance of 50 ± 20 nm, as compared to ~ 200 nm on large Si(001) areas. The periodicity is far from perfect, as seen in Fig. 1(b). The deviation from perfect periodicity is due partly to the undulations of the facets as a result of misorientation during the lithography.

While on a given stripe the distribution of ordered islands is monomodal, the *shape* is observed to change with stripe width. On large stripes the shape of islands is an elongated dome [Fig. 1(b)] while on narrow stripes the shape is a trapezoid- based pyramid. Figure 2(b) shows that the width of the islands decreases slightly from 150 to 130 nm, but the height decreases strongly, leading to a variation of the aspect ratio from $\alpha \sim 0.19$ for the elongated domes on stripes larger than 10 μm to $\alpha \sim 0.04$ for the irregular pyramids on the narrowest stripes. This decrease of height must be due to the smaller amount of Ge available for nucleation on the narrow stripes.

IV. PHOTOLUMINESCENCE OF RANDOM AND ORDERED ISLANDS

A. General features

Figures 3 and 4 display the spectral distribution of PL of several samples with unpatterned and patterned areas. A general feature of all spectra is that the no-phonon (NP) and transverse-optic (TO) phonon assisted emission from islands and from the wetting layer (labeled 2D) are well resolved. While the unpatterned area gives information only about the (001) plane, the arrays of stripes contribute in addition with emission from the $\{h10\}$ facets. The problem is to separate these contributions. The most important contribution from ordered islands is from those stripes which have only facets (see Table I). This will be discussed in more detail in the next subsections. Before that, features occurring in all spectra will be analyzed.

The TO phonon energy of the 2D layer is ≈ 58 meV, which is the value of the TO phonon in Si,[14] implying a penetration of the carrier wave function into the Si below and above. This is to be expected due to the small thickness of the 2D layer. The TO phonon energy for shallow islands (height below 10 nm) is ≈ 58 meV, but in thick islands it decreases to 48 meV. This mode may be the TO_{Si-Ge},[14] indicating a better confinement of the wave function to the island region. Since the islands contain $\sim 50\%$ Si, as predicted for a deposition temperature of 700 °C,[15] the TO_{Si-Ge} rather than the TO_{Ge-Ge} are expected to occur.

The transverse-acoustic (TA) phonon assisted PL energy of the 2D layer occurs as a clear peak in several stripes, which means that the wetting layer is uniform in those samples. For instance, in Fig. 3(a) all stripes $\leqslant 30$ μm show the TA peak (14–17 meV).

The $TO+O^{\Gamma}$ peak of silicon at 1033 meV[16] is often observed as a narrow peak [for instance in Fig. 3(a) the unpatterned and 300 μm stripes and in Fig. 4(b) the 4 and 2 μm stripes]. The NP peak of the 2D layer is sometimes near the Si 1033 meV peak and this needs a careful deconvolution of the peaks.

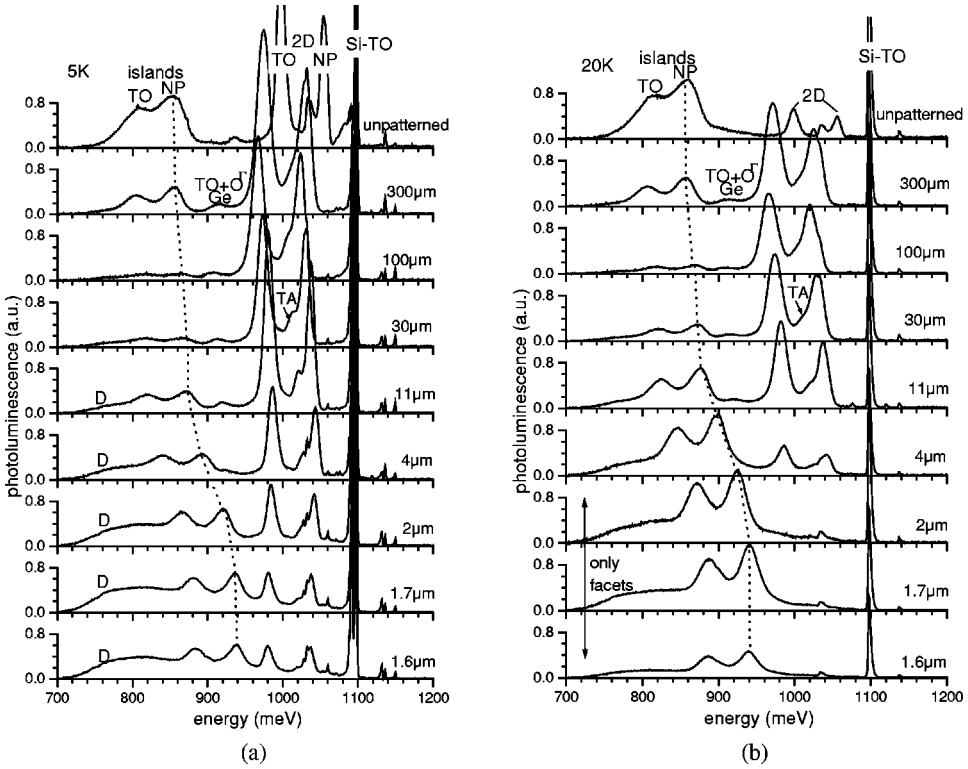

FIG. 3. Spectral distribution of photoluminescence of an unpatterned area and of arrays with mesa stripes with islands (No. 1594): (a) 4 K and (b) 20 K. The peak labeled Si-TO is from the substrate and lies at 1097 meV.

A peak labeled TO+O$^{\Gamma}$(Ge) at ≈117 meV below the NP–2D peak occurs systematically, shifting with the NP–2D peak. It is observed in almost all spectra (when it is not below another peak). This peak may be attributed to the TO+O$^{\Gamma}$ of the 2D layer.

By decreasing the mesa width a broad peak at low energy occurs and increases in intensity. It is present even for mesas without islands. This deep luminescence band, labeled D, will be discussed further in Sec. IV F.

B. Influence of facet width

The sample in Fig. 3 shows a blueshift of the island emission with decreasing stripe width. To see if this shift is related to the facets, two samples with larger facets were deposited (Nos.1602 and 1604, see Table I). This was achieved by depositing thicker buffers. An increase of the buffer thickness causes facets to grow larger[10] and therefore to lead to a disappearance of the (001) plane already at larger

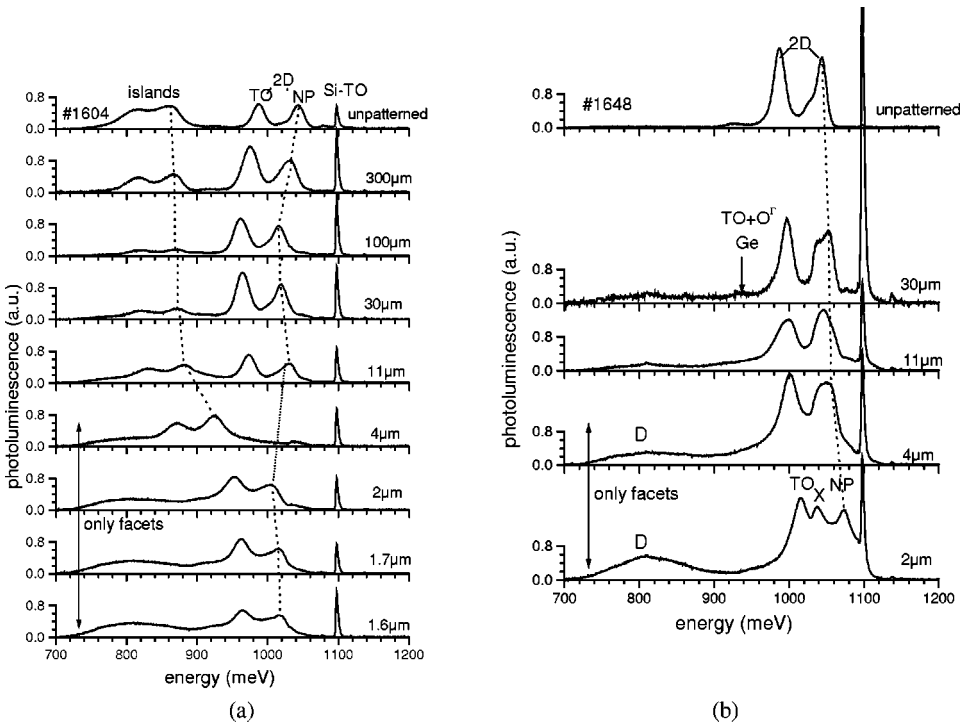

FIG. 4. Spectral distribution of PL for two samples measured at 20 K: (a) sample with islands (No. 1604) and (b) sample with only 2D layer (No. 1648). The PL intensities in (a) and (b) and in Fig. 3 can be compared because the scale is the same.

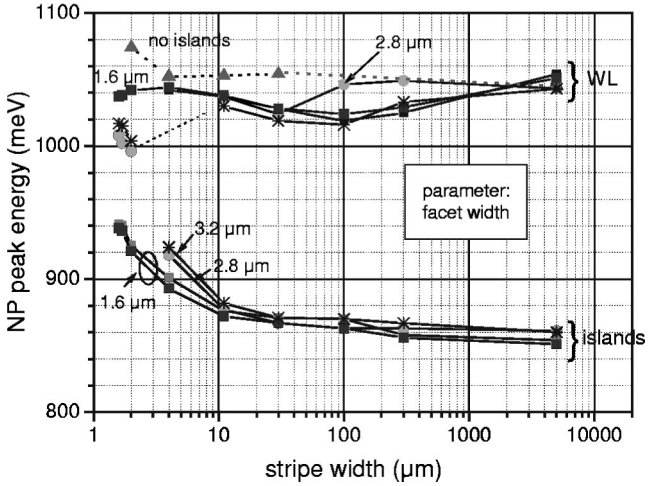

FIG. 5. Energy of NP peaks from Figs. 3 and 4 of wetting layer and of islands depending on mesa linewidth.

stripes. Indeed the 4 μm stripes of these samples have no (001) plane in contrast to the sample of Fig. 3.

Figure 4(a) displays spectra at 20 K of a sample with a thicker buffer, i.e., with larger facets (No. 1604). We observe that the evolution of emission with decreasing width is similar to that of the sample with a thinner buffer [Fig. 3(b)]. The NP peak positions of islands and the wetting layer are represented in Fig. 5. For samples with a thicker buffer, i.e., with larger facets, the blueshift of the island emission is stronger. Since this blueshift occurs for stripes of 11 μm or narrower, which as we have seen have only ordered islands, it is obvious that it is related to the ordered islands. This will be discussed in the next section.

Another detail in Fig. 4(a) is the disappearance of one pair of peaks on the narrower stripes. The question arises: is the remaining pair to be attributed to islands, or to the wetting layer? There are two reasons which plead for an emission from the 2D layer. First, the intensity ratio is $I_{\mathrm{NP}}/I_{\mathrm{TO}} < 1$. All 2D PL in Figs. 3 and 4 for stripes larger than 11 μm have a ratio smaller than one, while for islands $I_{\mathrm{NP}}/I_{\mathrm{TO}} > 1$. Second, AFM investigations on a sample without a cap have shown that there are no islands on stripes narrower than 2 μm. The reason for an absence of nucleation of islands must be that the amount of Ge on these stripes corresponds to a thickness smaller than the critical thickness for island nucleation, h_{SK}.

To conclude, the blueshift of the island PL is related to the ordered islands. Moreover, for the coverage used here no nucleation occurs on narrow stripes with large facets, although on larger stripes islands have nucleated. For higher coverage we expect islands even on the narrow stripes.

C. Hole transfer from the 2D layer to the islands

Figure 3 shows PL spectra measured at two temperatures of sample No. 1594 (facet width ~ 1.6 μm). While at 4 K the NP and TO emission from islands (3D PL) and the NP and TO emission from the wetting layer (2D PL) occur for all arrays, at 20 K the 2D PL disappears for widths $\leqslant 2$ μm. The disappearance of the 2D PL seems to be correlated to the blueshift of the 3D PL, which is, at least partly, due to the reduction of the island height [see Fig. 2(b)]. We have seen that ordered islands with a large height have an aspect ratio of ~ 0.19 which, after Gray,[12] would signify that these islands are on the top surface partly relaxed elastically, while at the edges the strain is tensile. This leads to a higher chemical potential and therefore to a thinner wetting layer around the island. This is equivalent to a potential barrier for holes in the wetting layer near the island, preventing the diffusion of holes to the island. For flat islands with a small aspect ratio of 0.04 this is different. Flat islands are almost coherently strained, there is no barrier for nucleation at the edge, and therefore no barrier for diffusion of holes from the wetting layer to the islands. At temperatures high enough for holes to diffuse along the wetting layer on distances of the order of the interisland distance but low enough for the holes in the island to remain trapped, holes confined to the 2D layer can become trapped in the flat islands and recombine there. For this reason the emission from the 2D layer reduces faster at higher temperatures in the stripes with flatter islands. This phenomenon is also observed in the sample with a thicker buffer for the 4 μm stripe [Fig. 4(a)]. Hole transfer from the wetting layer to self-ordered SiGe quantum wires was already evidenced by Hartman *et al.*,[17,18] leading to an increase of PL intensity of the quantum wires at low temperatures.

To conclude, holes confined in islands with a high aspect ratio are separated by a potential barrier from the wetting layer, preventing the hole transfer to the islands.

D. Photoluminescence of ordered islands

We have seen in the previous sections that ordered islands emit light, as random islands on Si(001) do, and that their emission intensities are comparable. A detailed comparison reveals in addition, that emission peaks from ordered islands are narrower than for random islands. We observe a decrease of the full width half maximum (FWHM) from 42 to 33 meV. This is obviously correlated to the monomodal distribution of ordered islands discussed in Sec. III, as opposed to the bimodal distribution of random islands. Ordered islands are more densely spaced, therefore elastic interaction between islands via a strained substrate causes an improvement of size uniformity.

One important feature is *the peak position* of ordered islands (Fig. 5). We expect quantum confinement only due to island height; confinement due to lateral size of the islands is not expected because the island diameter is over 100 nm. The peak position is given mainly by the quantum well thickness (in this case the island height) and by the band offsets (determined by strain and Si content). Stripes < 11 μm have only ordered islands. For the 11 μm stripes the peaks are only little blueshifted in comparison to those of random islands. However, for stripes < 11 μm there is a strong blueshift of ~ 80 meV. A blueshift can result by a decrease of island height, by a reduction of strain, or by an increase of Si content. First, a decrease of the island height is indeed observed for stripes below 11 μm, as seen in Fig. 2. A

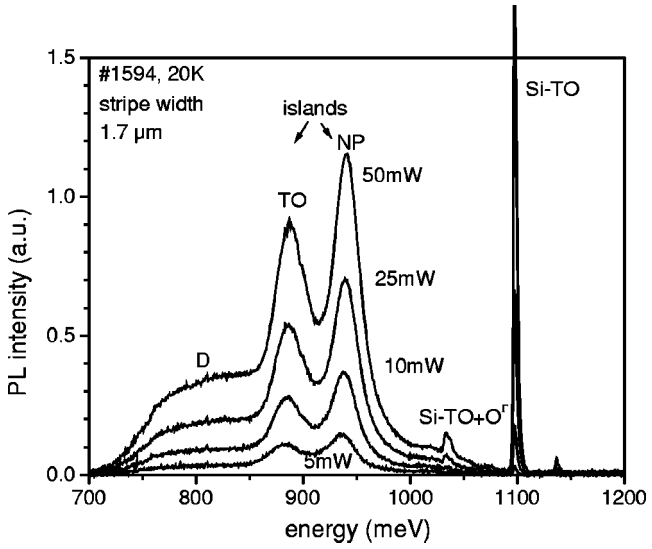

FIG. 6. PL spectra at 20 K for the 1.7 μm stripe of sample No. 1594 for different excitation powers. It is seen that the blueshift is $\sim$4 meV for a variation of factor of 10 of the excitation power.

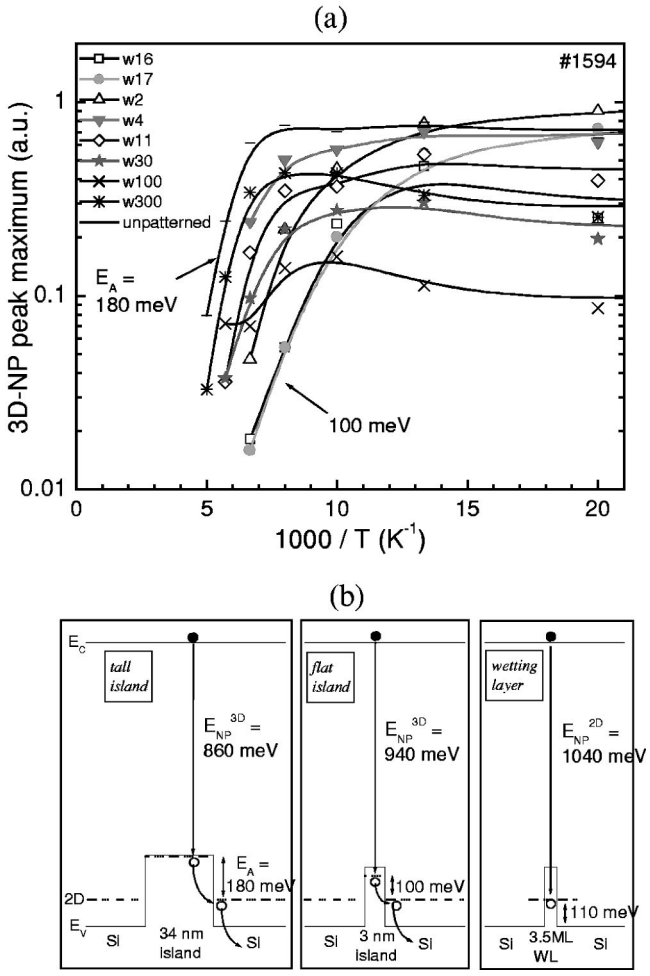

FIG. 7. (a) Temperature dependence of the maximum of NP peak of island emission measured at 50 mW for sample No. 1594 for different mesa widths. The activation energy decreases with decreasing width. (b) Schematic of band alignment for a tall island, a flat island and for the wetting layer; the dotted lines represent the first confinement level.

decrease of the height from 34 to 6 nm increases the confinement energy from $\sim$1 to $\sim$25 meV (we have assumed that holes are in a finite quantum well with $m^*_{hh}=0.245$ and $\Delta E_V=290$ meV). However, we have to keep in mind that capping decreases the island height.[19] Thus, assuming a reduction by a factor of 2 of the height, the confinement energy would increase from $\sim$4 meV (for 34 nm/2) to $\sim$75 meV (for 6 nm/2). Therefore, the blueshift can be attributed to the decrease of the island height.

Second, let us consider the strain of the islands. The islands with the blueshifted peaks are those with an aspect ratio lower than 0.07. Whereas the islands on the 11 μm stripes have $\alpha\sim0.17$, islands on the 1.6 μm stripes have $\alpha\sim0.04$ and their peaks lie $\sim$80 meV blueshifted. After Gray,[12] islands with an aspect ratio $\alpha\sim0.03$ are almost compressed, while for higher aspect ratios, i.e., $\alpha\sim0.18$, islands are half elastically relaxed. Islands almost compressed have a lower band gap than islands elastically relaxed. But, this would lead to a redshift of the PL peaks.

Third, it is generally agreed that Si interdiffusion plays an important role in island shape.[20] For 700 °C Capellini *et al.* evaluated a Si content of $\sim$50%.[15] For the flat islands ($\alpha<0.07$) to have a NP peak at higher energy we are bound to assume that the interdiffusion is stronger than in the ''balled-up'' islands.

The band-filling effect could also shift the PL peaks to higher energy.[21] Figure 6 shows the laser power dependence of the emission from ordered islands on the 2 μm stripes. The shift over 1 order of magnitude of excitation power is $\sim$4 meV. For other stripes this shift lies between 4 and 10 meV, however in a nonsystematic manner. An estimation of band-filling effect made by Baier *et al.* assuming a filling of $\Delta p=10^{11}$ cm^{-2} leads to an energy shift of the hole quasi-Fermi level of only a few meV.[21] Thus, our experimental results and the theoretical evaluations show that the band filling makes only a small contribution to the blueshift.

The temperature dependence of the 3D PL is represented in Fig. 7(a). There is an obvious decrease of the activation energy with decreasing stripe width, i.e., with decreasing island height. The highest activation energy is $E_A=180$ meV for the unpatterned area, and the lowest is $E_A=100$ meV for the ordered islands with height $h=3$ nm (see above). For the tall islands we write [see Figs. 5 and 7(a)]: $E_{NP}+E_A=860+180=1040$ meV. This is approximately the same as for the flat islands: 940+100 meV=1040 meV, but smaller than the Si band gap (1150 meV). It follows that the activation energy is $\sim$100 meV lower than the expected value in both cases. Thus, $E^{3D}_{NP}+E_A\approx E^{2D}_{NP}$. This result is consistent with the band alignments shown in Fig. 7(b), and with a recombination model in which an electron from the conduction band recombines with a confined hole in the valence band of the island. The activation energy is given by the energy difference between the confinement level in the island and the wetting layer. This means that the holes from islands are thermally excited with an activation energy of 180–100 meV to the wetting layer and from there, with a smaller activation energy to the Si barrier.[22,23]

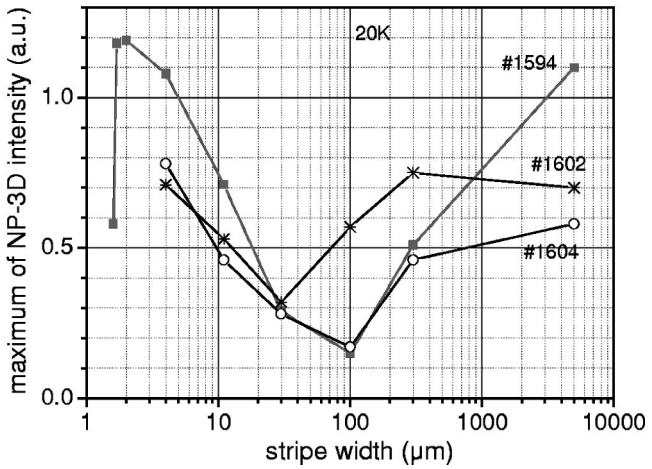

FIG. 8. Dependence of the NP peak maximum of islands on mesa stripe width for three samples with islands described in Table I.

We discuss now the evolution of PL intensity of islands with mesa stripe width (Fig. 8). By decreasing the width the PL intensity of islands first decreases then increases. In earlier investigations we have shown that the electroluminescence intensity of multilayers with vertically correlated islands increases if the total number of islands is higher.[8,24] To see if the variation of PL intensity in the present case is related to the island number, too, we compare the evolution of the maximum of the 3D NP peak with stripe width with the evolution of the total number of islands on an area of $1\,\mathrm{mm}^2$ [i.e., on the (001) part of the mesa plus those on facets], shown in Fig. 2(a). One can see that the NP intensity and the total number of islands show a similar evolution with stripe width: a decrease and then an increase. The minima correspond to those stripes that still have islands on the (001) part, while for stripes $\leqslant 30\ \mu$m mainly ordered islands exist. Their number increases when mesa width decreases and so does the PL intensity. It is difficult to present more than this qualitative behavior, since it is not yet clear which islands emit light. Goryll *et al.*[25] have shown that mainly dome shaped islands (width ~ 150 nm, height ~ 25 nm) emit light. This result is valid for islands nucleated on (001)Si at $T_{\mathrm{epi}} = 700\,^{\circ}\mathrm{C}$. We see here that at low temperature the emission from ordered islands is as high as the emission from random domes which have $\alpha \sim 0.19$. Therefore, the PL intensity scales approximately with the island number. The lower intensity for ordered islands on the narrowest stripe of 1.6 μm must be due to the fact that there are only flat pyramid-like shape islands [see Fig. 1(b)] which according to Goryll *et al.* have a weak emission.

E. Photoluminescence from {*h*10} facets

The ordered islands nucleate in the present experiments on {12 1 0} facets. These facets can be regarded as being composed of large (001) terraces and {110} steps. The critical thickness for island formation on the {110} surface is $h_{SK}(110) \approx 3.5$ ML.[26,27] Given $h_{SK}(110) \approx h_{SK}(001)$ we admit this to be valid for the {12 1 0} planes, too. With this premise we now analyze the contribution to PL of the facets.

The sample in Fig. 3 has islands on the 1.6 μm stripe, but only ordered ones. Stripes of 2 μm and less have only facets. Therefore, the 2D peaks of these stripes can be assigned to the facets. We observe $E_{\mathrm{NP}}^{\mathrm{2D}}$ (1.6 μm) $\approx E_{\mathrm{NP}}^{\mathrm{2D}}$ (unpatterned) in Figs. 3(a) and 5. This implies that on facets the thickness of Ge is 0.5 nm, as on the (001) plane, and not lower as we would expect from the lower growth rate on facets. This can be understood intuitively by a diffusion of Ge from the islands to the wetting layer to attain the value of h_{SK}, leading to a reduction of the island height. This leads to the same peak position of the 2D PL on facets as on unpatterned areas, but to a blueshift of the island peaks. However, if the overall amount of Ge is below h_{SK}, the peak positions on stripes will differ from that on the unpatterned area.

F. Deep luminescence band

In the energy range of 780–800 meV a peak labeled *D* and with a FWHM of ~ 100 meV occurs in all samples with islands [Figs. 3 and 4(a)] but also in the spectra of the stripes without islands [Fig. 4(b)]. For these stripes $d_{\mathrm{Ge}} \leqslant h_{SK}$, therefore we exclude islands as being the origin of this peak, at least in the present samples. One feature of this *D* band is that it occurs in stripes of 30 μm width and narrower, and is probably related to the strained Si mesas. The origin of this peak is currently under investigation.

V. CONCLUSIONS

Single rows of ordered islands nucleated on Si mesa stripes show a monomodal distribution in contrast to the bimodal distribution on unpatterned (001) Si. The shape of the ordered islands is an elongated dome on large mesa stripes, while on narrow mesas the islands are irregular pyramids. The achievement of the equilibrium shape is faster for islands at edges than for islands on the (001) plane. The linear ordering reflects, as a fingerprint, the existence of a linear row of tensile strained sites on Si mesa edges with a lower energy barrier for nucleation than on the (001) plane. The PL peaks from islands are well resolved. The effect of ordering is to narrow the NP and TO peaks. The PL intensity seems to be proportional to the island number and is as high as for the random islands, as long as the islands are dome like. The evolution of PL intensity with island shape and with temperature is governed by hole transfer between the wetting layer and islands. The island height decreases on the narrow stripes, shifting the peaks to higher energies and decreasing the activation energy. Higher coverage is expected to avoid these effects. We demonstrate that the deep luminescence band at 800 meV occuring on narrow mesas is not originating from islands. Finally, there are two reasons for using narrow stripes with ordered islands. The first one is that ordered islands are more uniform in size, therefore the PL peaks are better resolved and narrower. The second reason is that ordered islands have a much higher linear density. This can be used to increase the areal density of islands by preparing samples with a high number of densely spaced and narrow stripes. As the PL scales approximately with the number of islands, this is a means to increase the luminescence intensity.

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