



**HAL**  
open science

## Optical characterisation of Ge islands grown on Si(110)

Philippe Ferrandis, L Vescan, B. Holländer

► **To cite this version:**

Philippe Ferrandis, L Vescan, B. Holländer. Optical characterisation of Ge islands grown on Si(110). Microelectronics Journal, 2002, 33 (7), pp.541-546. 10.1016/S0026-2692(02)00016-2 . hal-01616513

**HAL Id: hal-01616513**

**<https://hal.science/hal-01616513>**

Submitted on 13 Oct 2017

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Optical characterisation of Ge islands grown on Si(110)

P. Ferrandis<sup>a,\*</sup>, L. Vescan<sup>b</sup>, B. Holländer<sup>b</sup>

<sup>a</sup>Laboratoire de Physique de la matière, UMR CNRS 5511, INSA de Lyon, Bât. Blaise Pascal, 7 Avenue Jean Capelle, 69621 Villeurbanne Cedex, France

<sup>b</sup>Forschungszentrum Juelich GmbH, Institut fuer Schichten und Grenzflächen, D-52425 Juelich, Germany

---

## Abstract

The growth of Ge islands on Si(110) substrates by low pressure chemical vapour deposition has been studied. Atomic force microscopy images reveal that multifaceted dome shaped islands appear on samples where the two-dimensional (2D) to three-dimensional (3D) growth mode changeover has occurred. Photoluminescence (PL) spectroscopy was used to investigate the growth as a function of the Ge coverage. The excitation power dependence of island PL spectra allowed one to point out a band filling effect and to determine the efficiency of radiative recombinations. In addition, island PL peak evolution with temperature underlined a good hole confinement. © 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** Si(110); Ge; Islands; Low pressure chemical vapour deposition; Atomic force microscopy; Photoluminescence

---

## 1. Introduction

Optoelectronic components fully integrated on Si constitute a driving force for cost reduction in fabrication processes. SiGe materials and particularly Ge nanostructures are used as a possible approach in this way. Thus, Ge islands embedded in Si are expected to produce an intense light emission due to the exciton localisation into them.

The growth of Ge islands on several Si surface orientations has been studied such as on (110) [1], on (111) [2] or on (113) [3]. The (110) orientation seems to provide advantages which might be interesting for the growth of self-assembled Ge dots. Indeed, the structural anisotropy of the Si(110) surface may influence the nucleation of coherent Ge islands. Furthermore, a reduced band gap for strained SiGe alloys resulting from a lower conduction band edge with type I alignment is expected [4]. This forecast should increase the electron confinement. From a technological point of view, the (111) cleavage planes perpendicular to the (110) surface may simplify the fabrication of waveguide structures.

In this paper, we present the characterisation of Ge islands grown on Si(110) substrates. Section 2 describes the experimental procedure, after which Section 3 introduces the island morphology. Then, a detailed photolumi-

nescence (PL) study is presented as a function of Ge coverage, temperature and excitation power.

## 2. Experimental

Epilayers were grown on *n*-type (110) oriented Si substrates (resistivity 1–10 Ωcm) in a low pressure chemical vapour deposition (LPCVD) reactor. Growth was carried out at 0.12 Torr using SiCl<sub>2</sub>H<sub>2</sub> and He-diluted GeH<sub>4</sub> as source gases for silicon and germanium epitaxy, respectively. After the deposition of a ≈250 nm thick Si buffer layer at 800 °C, Ge dot structures were grown at 700 °C with a constant pure GeH<sub>4</sub> flow of 1 sccm. Samples used for PL investigations were capped by a Si layer deposited at 700 °C for 60 min in order to avoid non-radiative recombinations which could take place at the surface of Ge islands. No annealing steps were performed between layer depositions, and samples were cooled after epitaxy with a cooling rate of 1 K/s.

The surface topography was investigated with a Digital Instruments Nanoscope IIIa atomic force microscopy (AFM) in tapping mode on samples without a cap layer. PL measurements were carried out using the 514.5 nm emission line of an argon-ion laser. A beam focused with a 200 μm diameter was used as excitation source. Luminescence was dispersed by a HRS2 Jobin–Yvon monochromator and detected by a liquid-nitrogen cooled Ge detector (Applied Detector Corporation 403L I-R). Rutherford back-scattering spectroscopy (RBS) analysis allowed determination of the total Ge amount deposited.

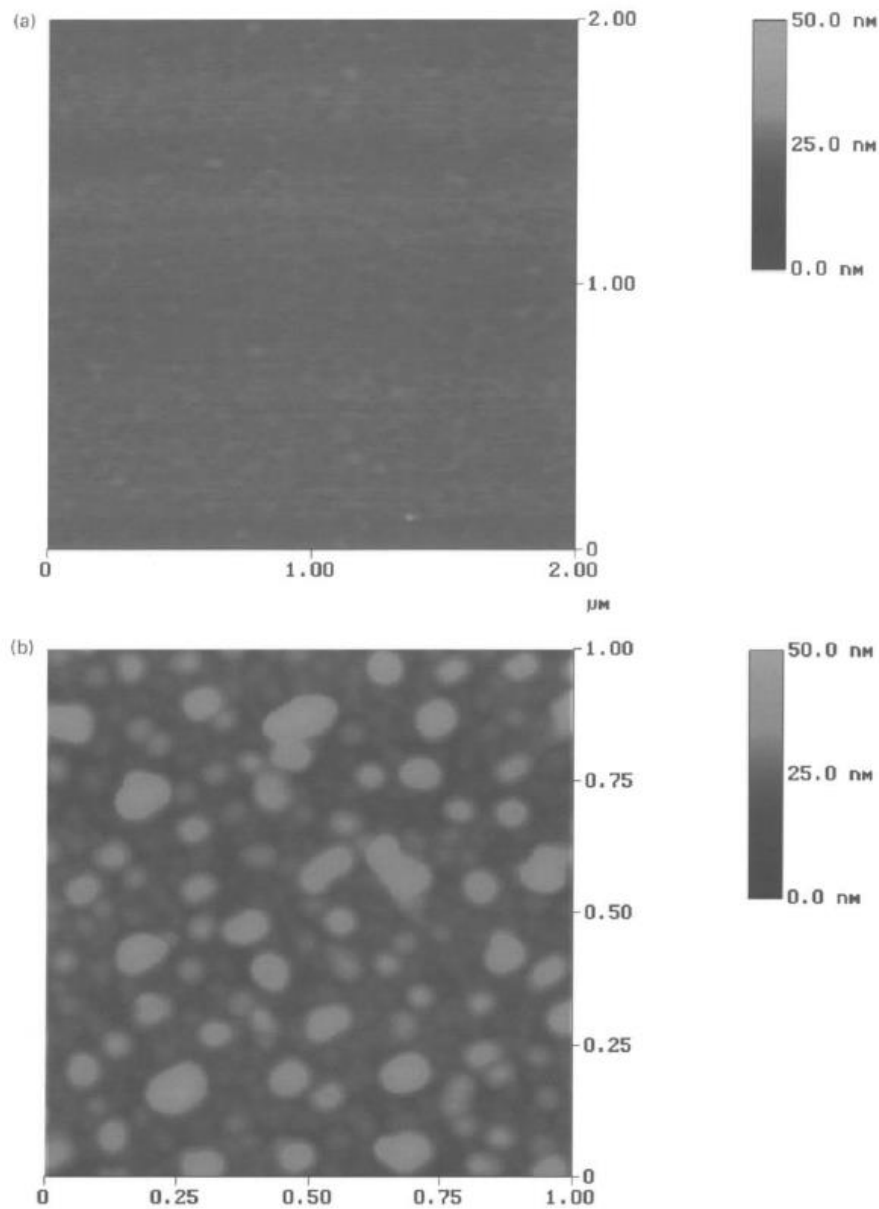


Fig. 1. AFM images (a) before and (b) after the 2D to 3D growth mode changeover. While a very flat surface is observed in (a) (Ge thickness = 3.4 ML), a large number of islands with a dome shape appears in (b) (Ge thickness = 5.3 ML).

### 3. Results and discussion

Capped and uncapped samples with various Ge coverages were performed on Si(110) substrates. The total Ge amounts were determined from RBS analysis and were in the range of 2.4 to 10.3 monolayers (ML) for uncapped samples (1 ML of Ge on (110) corresponds to 0.2 nm). The two-dimensional to three-dimensional growth mode changeover occurred for a Ge equivalent number of ML between 3.4

and 5.3. Fig. 1 presents two AFM images. The first (Fig. 1a) shows the surface topography before the 2D to 3D transition (Ge thickness = 3.4 ML). The surface is relatively flat (roughness inferior to 2 nm) and no islands are present. In the second image (Fig. 1b), the 2D to 3D transition has occurred (Ge thickness = 5.3 ML). A large number of islands (density  $\approx 81 \mu\text{m}^{-2}$ ) with an average height of 16 nm (Fig. 2a) and an average diameter of 89 nm (Fig. 2b) can be observed. Despite the proximity to the 2D

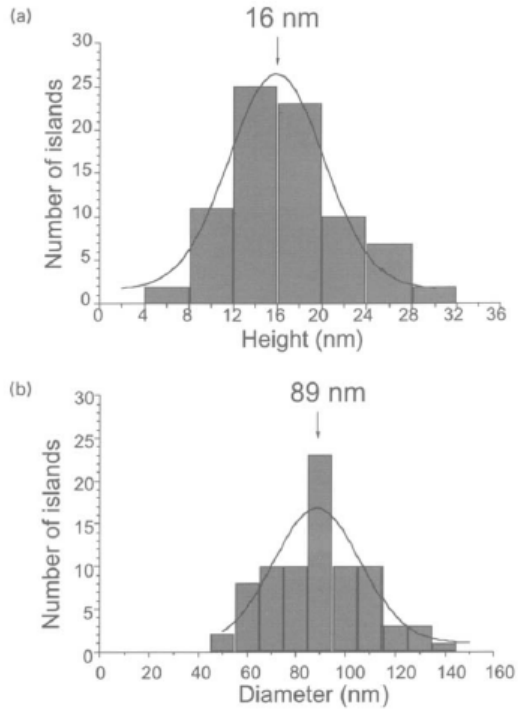


Fig. 2. Island height (a) and diameter (b) distribution from sample with a total Ge amount of 5.3 ML. The monomodal distribution reveals that only one kind of islands grows.

to 3D transition, a monomodal island size distribution revealing the presence of only one kind of islands could be identified (Fig. 2). These islands are domes since their shape is rounded and they exhibit multiple equilibrium facets [5]. Smaller islands which usually appear in the early stage of the growth on Si(001) [6] or on Si(111) [7] for example, were not observed on our samples grown on Si(110). Such islands seem to be not sufficiently stable, and domes grow at their expense [7].

In Fig. 3, four PL spectra performed at 5 K with an excitation power density of  $5 \text{ W/cm}^2$  are shown. They were performed with capped samples which had the same growth conditions as the uncapped samples A, B, C and D. The four uncapped samples have a total Ge thickness of 2.4, 3, 9.7 and 10.3 ML, respectively (see Table 1). However, the Ge thicknesses of the capped samples were found smaller. 0.25, 0.4, 0.5 and 0.5 ML have been determined for the capped samples equivalent to the A, B, C and D uncapped samples, respectively. A size reduction of island heights caused by the growth of a cap layer has already been observed on Si(001) [8]. On Si(110), this size reduction is assisted by a severe loss of Ge atoms which is still under investigation. Nevertheless, the growth mode of Ge is not changed since islands are still present after the overgrowth.

On all spectra, PL contributions above 1020 meV originate from the silicon layers. Consequently, the discussion is

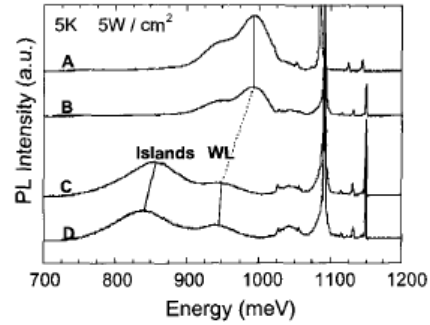


Fig. 3. PL investigations as a function of Ge coverage. Spectra of capped samples A and B are dominated by the 2D Ge layer PL. The 3D growth occurs for a Ge coverage between the one of samples B and C (as determined by AFM analysis) since spectra of capped samples C and D exhibit an island PL emission.

focussed on the PL signal between 700 and 1020 meV, which is dominated by Ge emission. Samples A and B do not contain islands since their Ge thickness is below the critical value of the 2D to 3D transition. The spectra of the capped samples A and B reveal only the PL of a 2D layer with a no-phonon (NP) peak and its transverse optic (TO) phonon replica at lower energy. Samples C and D have a sufficient Ge amount to exhibit islands whose features before capping are given in Table 1. The spectra of the capped samples C and D constitute by two broad peaks. The one near 945 meV is attributed to the wetting layer PL while the other one at lower energy is due to the island PL.

Following the wetting layer PL when the Ge coverage increases, we note that its intensity decreases when islands appear. This means that excitons are more easily trapped by islands which have a better energy confinement than the wetting layer [9]. On the other hand, the island PL intensity is higher than the PL of the wetting layer on both the capped sample C and capped sample D spectra. The large island area density could be the cause of this feature. For instance, with an island density of  $84 \mu\text{m}^{-2}$ , about 2/3 of the surface of sample D is covered by islands. The diffusion length of carriers is therefore sufficient to allow the possibility of excitons reaching an island.

In the capped sample B spectrum, the NP peak of the 2D layer is located at 992 meV and moves to 943 meV in the capped sample C spectrum. Such a shift is consistent with a previous study which assigns it to a quantum confinement effect caused by the increase of the 2D layer thickness [10]. The PL evolution between the capped samples A and B and between the capped samples C and D are not discussed since the size reduction during the cap layer growth is still unclear and needs further investigation.

Fig. 4 shows the PL spectrum of the capped sample D at 300 K under an excitation power of  $500 \text{ W/cm}^2$ . The island PL peak is observable in this spectrum while the wetting layer PL contribution has disappeared. A PL signal at room

Table 1

Detailed features of four uncapped samples. The Ge thicknesses were determined from RBS analysis and expressed in equivalent number of ML. Densities and average island heights were deduced from AFM investigations

Sample name	Ge thickness (equivalent-ML) (RBS)	Island area density ( $\mu\text{m}^{-2}$ ) (AFM)	Average island height (nm) (AFM)
A	2.4		
B	3		
C	9.7	45	27
D	10.3	84	22

temperature proves that islands exhibit a good hole confinement implying a barrier for thermal emission that is sufficiently high to keep the holes inside quantum wells. When the temperature increases from 5 K the diffusion length of the carriers increases. Consequently, carriers can easily move from the wetting layer to be incorporated into islands which are energetically more favourable. For this reason, the island PL persists when temperature increases at the expense of the wetting layer PL which vanishes.

In Figs. 5–7, we show an excitation power dependence of the island PL peak of the capped sample D spectrum. A temperature of 70 K was chosen to avoid the wetting layer PL contribution, without breaking the excitonic character of recombinations. Fig. 5a reveals a peak widening when the excitation power increases from 1 to 3000  $\text{W}/\text{cm}^2$ . Such a trend results from a band filling effect [11]. Carriers participating in PL no longer need be at the band edge extremes and the recombination energy increases. However, guide lines in Fig. 5a indicate that this peak broadening is not significant up to 60–70  $\text{W}/\text{cm}^2$ , and becomes stronger with a slope of 8.6 meV per decade after this threshold.

One explanation could be that above this critical power value, the laser beam creates a sufficient carrier density to push the quasi Fermi levels into the bands and produce an increase in band filling [11].

A more likely explanation for this non-linear excitation

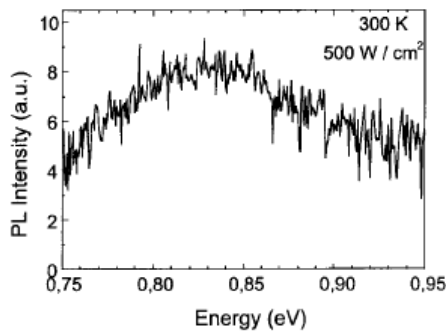


Fig. 4. PL spectrum of capped sample D performed at 300 K. An excitation power of 500  $\text{W}/\text{cm}^2$  was used. The energy scale has been focused on the low energy part of the spectrum during measurements to take advantage of an enhanced sensibility.

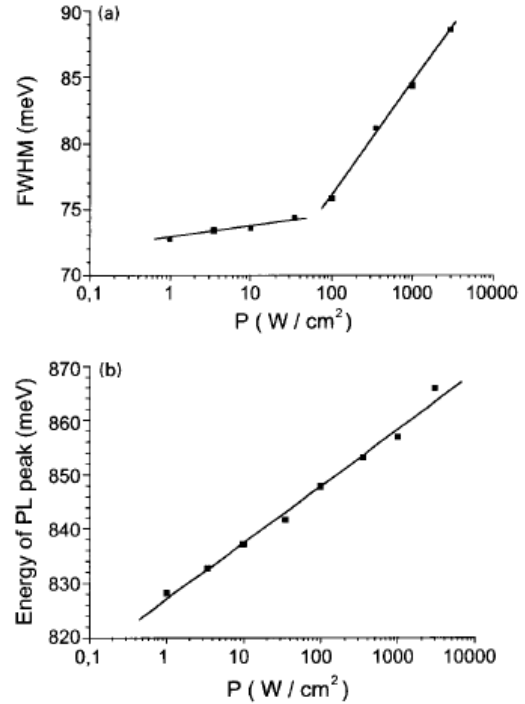


Fig. 5. Excitation power dependence of (a) the island PL peak FWHM (full width at half maximum) and (b) energy for capped sample D. Measurements were performed at 70 K. Solid lines in (a) are just guides for eyes. The straight line in (b) comes from a linear fit.

dependence of the width could be the presence of two peaks with a small separation in energy  $\Delta E$ . At high excitation power the width of these peaks is higher than  $\Delta E$ . When the excitation power decreases, their widths become smaller than  $\Delta E$  and the width of the peak resulting from their superposition decreases much more slowly. As AFM images analysis leads to only one island size distribution, these two PL peaks with approximately the same energy cannot be explained by the PL of two island populations. In addition, the broadening cannot originate from the separation of NP and TO lines at low excitation power since the shape of the left part of the spectrum does not change when the excitation power decreases (see Fig. 6a). Several authors have reported that for low power excitations the PL of localised excitons appears at lower energy than the PL of free excitons [12–15]. However, this PL disappears quickly when temperature increases [14,15]. As our experiment has been done at 70 K, the PL contribution of localised excitons is less likely. Moreover, Fig. 6b shows that no change is seen on the left part of a spectrum done at low power excitation when the temperature decreases from 70 to 9 K. While one peak is attributed to PL island emission the origin of a second peak, which could explain the larger width of the spectrum at low power excitation is not yet well understood.

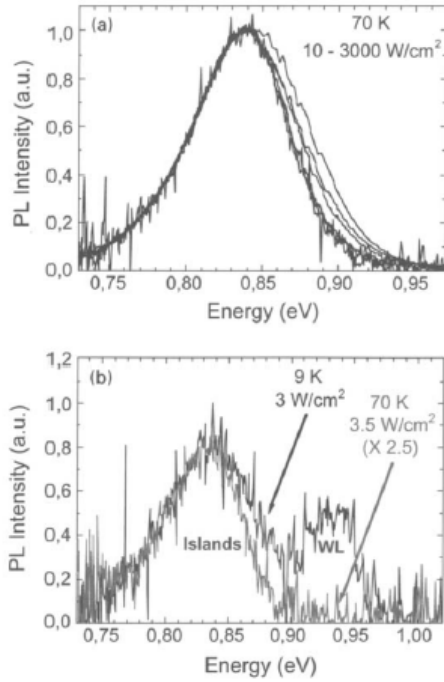


Fig. 6. (a) Superposition of capped sample D spectra performed with an excitation power of 10, 35, 100, 350, 1000 and 3000 W/cm<sup>2</sup>. After a normalisation to 1, each spectrum has been shifted in energy to superpose all maxima of island PL peaks. The left part of the spectrum does not change when the excitation power increases. (b) Comparison of two capped sample D spectra performed at 10 W/cm<sup>2</sup>, one at 9 K and the other at 70 K. The intensity of the spectrum performed at 70 K has been multiplied by 2.5. No shift has been done.

The peak PL energy as a function of the laser power shown in Fig. 5b confirms that a band filling effect takes place since a blue shift is observed [11,16].

In Fig. 7, we have plotted the integrated PL intensity of the island PL peak against the excitation power. Results

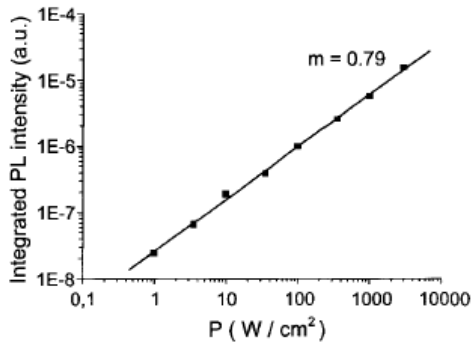


Fig. 7. Excitation power dependence at 70 K of integrated PL intensity for capped sample D. The power exponent extracted from the slope  $m = 0.79$  reveals the presence of non-radiative channels.

were fitted with Eq. (1)

$$I_{PL} \propto P^m \quad (1)$$

where  $I_{PL}$  is the integrated island PL intensity,  $P$  is the excitation power and  $m$  is the power exponent. The slope  $m = 0.79$  is smaller than 1 which is the expected value for pure excitonic recombinations. This sublinear exponent cannot be explained by bound exciton recombinations since all excitons are free at 70 K. Thus non-radiative pathways should consume carriers [17]. However,  $m$  remains constant between 1 and 3000 W/cm<sup>2</sup>. This trend has already been observed by other authors [17] and indicates that non-radiative channels have been quenched. Consequently, the luminescence comes mainly from radiative recombinations.

#### 4. Conclusion

Ge islands have been grown on Si(110) substrates. AFM investigations report that islands formed on the surface are domes with multiple equilibrium facets. With an average area density of 81  $\mu\text{m}^{-2}$  for a total Ge thickness of 5.3 ML, islands reach an average height of 16 nm. A Ge coverage dependence of PL spectra allows one to conclude that islands act as a strong carrier trap. This trend is mainly explained by the large area covered by islands on the surface. The PL signal still detectable at room temperature also indicates a good hole confinement into islands. Furthermore, the PL spectra evolution versus the excitation power leads to the conclusion that island luminescence comes actually from excitonic recombinations. Finally, a non-linear behaviour of the island PL peak width as a function of the excitation power could indicate either the entry of the quasi Fermi levels into the bands from a threshold power value of about 60–70 W/cm<sup>2</sup> or the presence of another PL emission at an energy similar to the island PL energy.

#### Acknowledgements

The authors are indebted to TMR Network Apples No. FMRXCT96-0029 for financial support. The first author expresses his great thanks to Dr R. Carius from Forschungszentrum Jülich and Dr C. Priester from Institut d'Electronique et de Microélectronique du Nord for fruitful discussions and useful comments. He also thanks Dr K. Smith for the correction of this article.

#### References

- [1] M. Krishnamurthy, B.-K. Yang, J.D. Weil, C.G. Slough, Appl. Phys. Lett. 70 (1997) 49.
- [2] P.D. Persans, P.W. Deelman, K.L. Stokes, L.J. Schowalter, A. Byrne, T. Thundat, Appl. Phys. Lett. 70 (1997) 472.
- [3] J.-H. Zhu, C. Miesner, K. Brunner, G. Abstreiter, Appl. Phys. Lett. 75 (1999) 2395.
- [4] C.G. Van de Walle, R.M. Martin, Phys. Rev. B 34 (1986) 5621.
- [5] D.J. Eaglesham, M. Cerullo, Phys. Rev. Lett. 64 (1990) 1943.

- [6] O.G. Schmidt, K. Eberl, *Phys. Rev. B* 61 (2000) 13721.
- [7] G. Capellini, L. Di Gaspare, F. Evangelisti, E. Palange, *Appl. Phys. Lett.* 70 (1997) 493.
- [8] P. Sutter, M.G. Lagally, *Phys. Rev. Lett.* 81 (1998) 3471.
- [9] L. Vescan, M. Goryll, T. Stoica, P. Gartner, K. Grimm, O. Chretien, E. Mateeva, C. Dieker, B. Holländer, *Appl. Phys. A* 71 (2000) 423.
- [10] J. Arai, A. Ohga, T. Hattori, N. Usami, Y. Shiraki, *Appl. Phys. Lett.* 71 (1997) 785.
- [11] J.C. Sturm, A. St. Amour, Q. Mi, L.C. Lenchyshyn, M.L.W. Thewalt, *Jpn J. Appl. Phys.* 33 (1994) 2329.
- [12] L.C. Lenchyshyn, M.L.W. Thewalt, J.C. Sturm, P.V. Schwartz, E.J. Prinz, N.L. Rowell, J.-P. Noël, D.C. Houghton, *Appl. Phys. Lett.* 60 (1992) 3174.
- [13] L.C. Lenchyshyn, M.L.W. Thewalt, J.C. Sturm, P.V. Schwartz, N. Rowell, J.-P. Noël, D.C. Houghton, *J. Electron. Mater.* 22 (1993) 2
- [14] J. Hartung, V. Higgs, G. Davies, E.C. Lightowler, V. Arbet-Eng K.L. Wang, *Jpn J. Appl. Phys.* 33 (1994) 2340.
- [15] U. Menczigar, G. Abstreiter, J. Olajos, H. Grimmeiss, H. Kibl H. Presting, E. Kasper, *Phys. Rev. B* 47 (1993) 4099.
- [16] M. Wachter, K. Thonke, R. Sauer, F. Schäffler, H.-J. Herz E. Kasper, *Thin Solid Films* 222 (1992) 10.
- [17] S. Fukatsu, N. Usami, Y. Shiraki, *J. Vac. Sci. Technol. B* 11 (1993) 895.