Effect of ion bombardment on deep photoluminescence bands in *p*-type boron-modulation-doped Si layers grown by molecular-beam epitaxy

I. A. Buyanova,* W. M. Chen, A. Henry, W.-X. Ni, G. V. Hansson, and B. Monemar
Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden
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Broad photoluminescence (PL) bands (about 100 meV full width at half maximum) in the energy range between 0.70 and 1.03 eV are shown to be a frequently occurring feature in *p*-type boron-modulation-doped Si epilayers grown at low temperature by molecular-beam epitaxy. It is shown that the presence of a particular broad band (BB) is critically determined by the bias applied to the substrate during the growth. This gives evidence that these deep PL bands are at least partly induced by ion bombardment during the growth. To clarify their origin, the effect of the hydrogenation and the influence of a magnetic field on the PL bands are studied. The results obtained indicate the existence of at least four types of radiative centers. The observed correlation between x-ray-diffraction and PL measurements suggests that some of the BB's could be related to macrodefects, such as defect clusters. The optically detected cyclotron resonance (ODCR) technique is used to specify the spatial location of the BB-related defects in the structures. Information on the dependence of the electron mobility on the growth conditions is also obtained by ODCR. An active role of the boron dopants in the formation of the defects giving rise to the BB's is clearly demonstrated by comparing results from undoped Si epilayers grown under similar conditions.

I. INTRODUCTION

With the development of modern epitaxial techniques, it has recently become possible to grow high-quality Si thin films and SiGe/Si heterostructures at low temperatures for improved and innovated devices based on the existing highly developed silicon technology. Molecular-beam epitaxy (MBE) is known as a well-established technique for such growth.[1] The low-temperature MBE process has, however, also brought an issue that some defects can be unintentionally incorporated in crystals during the growth due to a low surface atomic migration rate. The situation can be more critical when energetic ions and dopants are also involved during the growth. On the other hand, ion beam processes have often been used during MBE in order to suppress dopant surface segregation and to enhance incorporation probability.[2,3] For example, for Sb, a common *n*-type dopant for MBE materials, the optimum control of the doping profile was achieved using ion bombardment. Doping techniques developed for this purpose include secondary ion implantation ($E_{\text{ion}}=500-2000$ eV, $J_{\text{ion}}/J_{\text{Si}}=10^{-2}-10^{-3}$),[4,5] and direct low-energy ion-beam doping ($E_{\text{ion}}=50-200$ eV, $J_{\text{ion}}/J_{\text{Si}}<10^{-3}$).[6]

By using recently developed high temperature effusion cells to sublimate elemental boron atoms,[7,8] very high doping concentrations ($[\text{B}]=1\times10^{21}$ cm^{-3}) and sharp profiles of B have been achieved for *p*-type doping. High surface concentrations of B, in case of δ-function doping, however, may still degrade the crystalline quality of a succeeding Si layer.[8]

Photoluminescence (PL) spectroscopy, as a sensitive and convenient (contactless) measurement method, has been widely used to characterize the crystalline quality of MBE-grown Si-based layered structures. The effects of the dopant ion energy and the growth temperature on the activation of the *p*-type doping and the material quality have also been investigated. It has been shown that the PL spectra of high-quality MBE-grown Si layers doped using low-energy ions are governed by sharp bound exciton lines related to doping impurities. In contrast, the low-temperature growth ($\sim$500 °C) primarily results in the appearance of deep broad bands PL (BB),[9] which are believed to arise from defects introduced during the growth. The nature of the defects responsible for these broad PL bands is still unknown. It is well known, on the other hand, that various broad PL bands can be present in bulk Si after electron irradiation,[10] ion implantation,[11,12] or reactive-ion etching.[13–15] Very recently, we have also observed similar PL BB's from MBE Si (Ref. 16) and SiGe (Ref. 17) layers grown at low temperatures (420 °C) with low-energy ion bombardment. Ion bombardment can occur during the MBE growth when ions presented in the chamber are accelerated by the built-up potential between the sample holder and *e*-beam evaporator. Therefore, radiation damage may be a common mechanism for the formation of the radiative centers responsible for the broad PL bands in different MBE Si epilayers. Bombardment should be of particular importance for the low-temperature growth due to in addition low surface adatom mobility. The use of a low growth temperature is often required for the following reasons. For the δ-doped Si structures an increase of the growth temperature higher than 450 °C leads to a strong broadening of the doping profiles and to an uncontrolled doping of the Si spaces, as it was shown by our secondary-ion mass-spectroscopy (SIMS) measurements. For Si/SiGe heterostructures a low growth temperature is required to

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secure sharp Si/SiGe interfaces for multiple quantum-well structures and to maintain a pseudomorphic growth of strained Si/SiGe structures.

In this paper we shall provide direct experimental evidence that the broad photoluminescence is indeed a common feature in Si epilayers grown by MBE with nonoptimized conditions. The formation of the BB-related centers is further shown to be strongly influenced by radiation damages during the growth. To control this process we used different bias applied to the Si substrate during the MBE growth. Such a bias can provide a barrier for the ions of a specific charge. An active role of the boron dopants in the formation of the BB's is clearly demonstrated. The results obtained for Si epilayers grown with different bias and doping conditions indicate the existence of at least four types of radiative centers, differing by the effect of hydrogenation and applied magnetic field. The observed correlation between the x-ray diffraction results and the PL measurements suggests that some of the BB's could be related to microdefects, such as defect clusters. The optically detected cyclotron resonance (ODCR) technique was used to specify the dependence of the electron mobility on the growth conditions.

The paper is organized in the following way. In Sec. II, we shall give a brief description of the sample preparation and the experimental procedures. The main body of the experimental results will be presented in Sec. III. The physical insights from the experimental results will be discussed in Sec. IV. Finally, in Sec. V, the most important conclusions will be summarized.

II. EXPERIMENT

All the structures studied in this work were grown using a Balzers UMS 630 MBE system, as previously described,[18] on Si(100) substrates, each having a 1000-Å undoped Si buffer layer. The structures consist of three periods of boron-δ-doped (1×10^{13} cm^{-2}) Si layers separated by 1000 Å of undoped Si spacers, capped with a 1000-Å Si layer. The growth temperature used for most of the samples is 420 °C. The reference samples were grown under the same conditions but without B doping. The total growth rate was 1–2 Å/sec. One main parameter varied during the growth is the parity and the strength of the bias applied to the Si substrate (from −1500 to +1000 V). The actual boron doping profiles were revealed by the SIMS and have a full width at half maximum ≤70 Å (limited to the SIMS depth resolution). For comparison, several additional structures were grown at 520 °C. According to the SIMS data, the dopant distribution in these structures is significantly broadened due to B surface segregation leading to a considerable doping of Si spacers. Therefore we shall hereafter focus only on the structures grown at 420 °C where the B-doping profile is know to be well defined.

Hydrogen passivation was accomplished at around 200 °C for 60 min, inside a quartz reactor with a remote dc H plasma at a pressure of 2.0 mTorr. The samples were replaced ∼15 cm away from the H discharge region to avoid damage due to ionic impact. The high-resolution x-ray diffraction studies were carried out to characterize the lattice strain and structure parameters of the samples, using a Philips MRD-1880 7-crystal diffractometer with the Cu $K\alpha$ lines ($\lambda=1.54$ Å) as the x-ray source. The PL measurements were performed at 2 K using either the 514.5-nm line or the UV multilines (333.6–363.8 nm) of an Ar^+ laser for PL excitation. The luminescence was first dispersed with a double grating monochromator and detected by a liquid-nitrogen-cooled North Coast Ge detector, and was finally recorded with the conventional lock-in technique in phase with the frequency of a mechanical chopper. The ODCR experiments were done at the X band (9.23 GHz) using a modified Bruker ER-200D electron spin resonance spectrometer, equipped with a TE_{011} microwave cavity with optical access in all directions. The sample temperature was around 6 K. The PL emission from the sample was monitored by a cooled Ge detector and synchronously detected with a lock-in amplifier in phase with the amplitude-modulated microwave field. The magnetic field dependence of the PL intensity was obtained with the aid of the magnet attached to the ODCR system, capable of reaching 1.5 T.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Photoluminescence

To elucidate the role of the ion bombardment in the formation of different defects during the MBE growth of modulation-doped structures, the PL spectra of Si thin films grown with different bias applied to the Si substrate during the growth are studied. Typical PL spectra recorded from these thin films are shown in Fig. 1. All

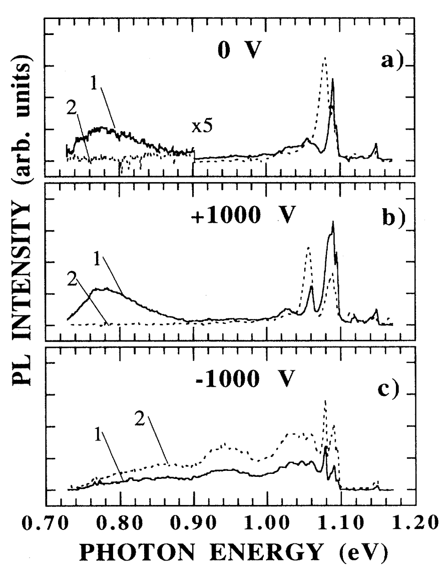

FIG. 1. Photoluminescence spectra of the B-doped Si epilayers grown with different bias applied to the substrate: (a) zero bias, (b) positive bias at +1000 V, and (c) negative bias at −1000 V. Spectra of the as-grown and the hydrogen-treated samples are shown by the solid and the dashed curves, respectively. The dip around 0.90 eV appearing in all spectra corresponds to the absorption by the water vapor.

spectra contain several deep broad PL bands, of which the peak positions and relative intensities strongly depend on the growth conditions. The phonon-assisted PL transitions detected below the shallow bound exciton emission were shown to be related to the radiative recombination of the free electrons and two-dimensional hole gas formed within the doped spikes, and will be discussed in detail elsewhere.[19] In addition, the substrate-related luminescence lines corresponding to the transverse optical phonon replicas of shallow bound excitons (1.092 eV), free excitons (1.097 eV), and electron-hole droplets (EHD's) are observed in the high-energy range of the PL spectra.[20] The intensity of the EHD's detected at 1.080 eV is increased after the postgrowth treatments such as thermal annealing or hydrogenation. These substrate-related PL emissions will not be discussed further in the paper.

For the Si epilayers grown with zero bias the PL spectrum contains a weak deep broad band in the spectral range of 0.70–0.90 eV [Fig. 1(a)]. The intensity of this band can be enhanced for the sample grown with positive bias [Fig. 1(b)]. The true peak positions of this band could be at lower energy than that experimentally observed ($\sim$0.78 eV), when the spectral response of the Ge detector is taken into account. In addition, a background emission in the spectral range 0.90–1.03 eV is detected. This PL band is the dominant emission for the samples grown with negative bias [Fig. 1(c)]. (It should be pointed out that the bias discussed throughout the paper refers to the bias applied to the substrate during the growth.)

The dependence of the PL spectra on the strength of the applied negative bias is depicted in Fig. 2. With increasing bias the intensity of the BB's increases. At -1500 V, this increase is accompanied by the appearance of sharp lines at 1.080, 1.0189, and 0.7689 eV, which are usually observed after ion implantation or similar surface treatments on bulk silicon,[20] consistent with a high energy of the bombarding ions. The dominant excitonic line at 1.080 eV is originated from B-related complex known to be produced by B implantation or electron irradiation of Si:B.[20]

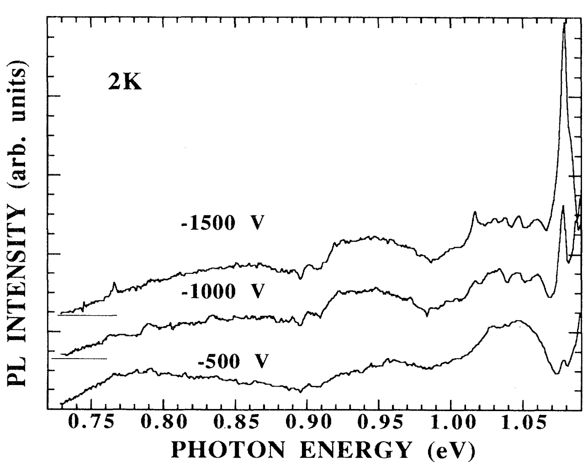

FIG. 2. PL spectra of the B-doped Si epilayers as a function of an increasing negative bias applied to the substrate during the MBE growth. The dip around 0.90 eV appearing in all spectra corresponds to the absorption by the water vapor.

A strong increase of the BB emissions observed for the samples grown with negative bias gives evidence that the BB's can be related to defects induced largely by the ion bombardment. As discussed in Ref. 16, the flux of the Si^+ ions of $(2-3)\times10^{12}$ cm^{-2} sec^{-1} is generated from the hot Si melt during evaporation by the electron beam. These ions can be accelerated when the substrate is negatively biased and cause radiation damage at the epitaxial surface. Various kinds of point and extended defects including complexes of point defects, defect clusters, and precipitates may be introduced in the epilayers, which are responsible for the BB emissions. According to the x-ray diffraction (XRD) measurements, the defects created due to bombardment by positive ions introduce compressive strain in the Si lattice. A local band-gap reduction is expected in such heavily damaged regions.[14] Thus, the observed luminescence could be partially attributed to the excitonic recombination in these distorted areas. A random distribution of the local strain fields around the different damaged regions will cause a random distribution of the electron-hole recombination energy, giving a very large half-width of the PL emission.

The presence of the 0.78-eV BB even in samples grown with zero bias indicates, however, that the corresponding defects can also be introduced without the ion bombardment. The creation of these residual defects is likely due to the low surface adatom mobility during the low-temperature MBE growth. The markedly different dependence on the growth conditions observed for the 0.78-eV band clearly indicates the different origin of the radiative centers introduced by the low-temperature growth and by the bombardment of negative particles. Further evidence will be given below using a number of complementary methods.

B. Hydrogen passivation

Hydrogen passivation of defects is known to affect directly their optical properties, and it is used here to distinguish different PL emissions. The PL spectra of the samples after the hydrogen passivation are shown in Fig. 1 as the dashed curves. As can be clearly seen from the figure, the 0.78-eV band detected in the layers grown with zero or positive bias is completely quenched by the hydrogen treatment [Figs. 1(a) and 1(b)]. In contrast, the high-energy BB's (0.90–1.03 eV) and low-energy emission from the layers grown with negatively biased substrates are unaffected by the hydrogenation process [Fig. 1(c)]. In addition, there is a general increase of the total PL intensity including the band-edge emissions observed for the hydrogenated samples. This increase can be attributed to a passivation of surface states, as well as a partial passivation of nonradiative recombination channels, which are very efficient in all structures studied, as is evident from our optically detected magnetic resonance measurements.[21]

It is well established that the sensitivity of defects to hydrogen treatment is determined by their structure.[22] Thus, the observed different response of the BB-related defects to the hydrogen treatment is an additional demonstration of their different origin. The known mechanisms of hydrogen passivation include simple ion pairing with point defects or the passivation of the dangling bonds.[22] The observed sensitivity of the 0.78-eV band to passivation implies that PL transitions are originated from point defects or complexes created during the low-temperature growth. The other emissions can be attributed to the excitonic transitions in the highly damaged areas with a reduced band gap, as well as to some point defects insensitive to hydrogen passivation.

C. Photoluminescence in a magnetic field

To elucidate the different origin of the various BB's, we carried out a study of the intensity of these BB's as a function of an external static magnetic field. The electronic structure and the recombination of the electronic excitation that gives rise to the PL emissions are in general known to be sensitive to external perturbations such as a magnetic field. In Fig. 3, we show the magnetic-field dependence of the PL intensity from the three representative samples discussed above. Two spectral ranges, i.e., 0.70–0.84 and 0.87–1.03 eV, were selectively monitored by using proper optical filters. It can be seen that the PL intensity within these two spectral ranges shows a noticeably different variation with the magnetic field from all these samples. Moreover, the behavior of the PL emissions from the sample grown with zero bias [Fig. 3(a)] resembles that from the sample grown with positive bias [Fig. 3(b)]. It should also be pointed out that the magnetic-field dependence of the PL emissions in the range 0.70–0.84 eV from the samples grown with negative bias [the upper curve in Fig. 3(c)] is qualitatively different from the others; i.e., it shows a monotonous sublinear increase rather than a monotonous decrease with increasing magnetic-field strength.

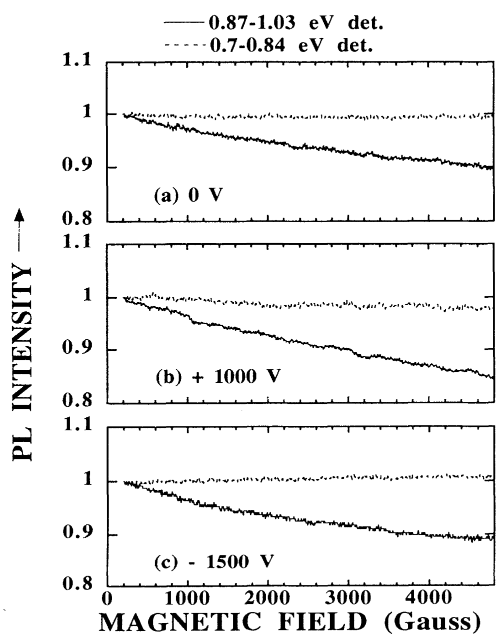

FIG. 3. The magnetic-field dependence of the PL intensity in two different spectral ranges from the B-doped samples grown with (a) zero bias, (b) positive bias, and (c) negative bias. The solid and dashed curves were obtained by monitoring the PL emissions in the spectral range 0.87–1.03 and 0.7–0.84 eV, respectively. The intensity is normalized at the lowest field.

The application of the magnetic field is known to affect in many ways photoluminescence of a semiconductor, strongly depending on the detailed nature of the photoluminescence emissions. Magnetic-field-induced resonantlike changes in the PL intensity have been mostly attributed to cross relaxation, an important mechanism for intercenter energy transfer, and also to level-anticrossing effects of an intracenter nature.[23,24] These mechanisms can be ruled out in this case, however, since no resonantlike feature has been observed in the experiments. On the other hand, the nonresonant variations of the PL intensity in a magnetic field have been discussed in terms of a magnetic-field-induced transverse compression of the ground-state wave function of the exciton,[25,26] the magnetic Stark effect,[27] a symmetry-breaking effect,[24] or a strong enhancement of surface recombination due to magnetic-field-induced confinement of photoexcited free carriers near the surface.[28] Since all these effects are sensitive to the electronic structure of the defect state and the mechanism of the recombination, it is expected that such a magneto-optical spectroscopy can be utilized as a diagnostic tool to distinguish one PL emission from the other. This can be accomplished even though the detailed recombination mechanism for a specific PL emission is not yet well understood.

Therefore, the differences in the behavior in the magnetic field of the PL emissions in the two spectral ranges from all the samples shown in Fig. 3 can be regarded as a direct experimental evidence for different origins of these PL emissions. The observed similarity between the samples grown with zero and positive bias [Figs. 3(a) and 3(b)] indicates that similar or even the same recombination mechanisms are involved. This in turn shows that the defects introduced during the growth with either zero or positive bias are rather similar. For the sample grown with the negative bias, the PL emissions in the range 0.87–1.03 eV behave quite similarly to that from the samples grown with zero and positive bias. The deeper PL emissions (0.70–0.84 eV) are, however, markedly different. A monotonous increase of the PL intensity with magnetic field in this spectral range from the sample grown with negative bias can most plausibly be attributed to an excitoniclike recombination, based on previous experimental facts.[25,26] These excitoniclike recombination processes can be due to either deep bound excitons related to the deep defects introduced by the ion bombardment or due to the free excitons in the spatial regions where the band gap has been reduced by the local strains as the consequence of the ion bombardment. These observations are consistent with the results from the hydrogenation treatments discussed in the previous section.

D. Optically detected cyclotron resonance

During the past years the ODCR technique has been rather successfully employed not only to extract the band-structure parameters of a semiconductor similarly to the case of the traditional CR study, but also to obtain information on hot carrier effects, recombination processes, and the interplay between them.[29] In this work we applied the ODCR technique to spatially locate the PL emissions that were monitored in the ODCR experiments. This can be done because the hot carriers involved contain detailed information on the band structure, which is very sensitive to any perturbation applied to the crystal by the strain due to the lattice mismatch or by the local strain field induced by extended defects.

It is well known that several CR peaks should be observed in an ODCR spectrum from silicon, corresponding to the number of inequivalent orientations of the six electron valleys from the conduction-band minima with respect to the direction of the external magnetic field. These CR peaks can be resolved if $\omega\tau \gg 1$ or equivalently the electron mobility is high,[23] where ω is the microwave frequency and τ is the electron scattering time. When $\omega\tau \leq 1$, the CR peaks become very broad and strongly overlap with each other. This results in an unresolved CR signal peaking at a magnetic field $B > \omega m^*_{\rm min}/e$, i.e., $B > 500$ G at 9.23 GHz in this case. Here $m^*_{\rm min}$ is the minimum value of the electron effective masses in Si.

In Fig. 4 we show the ODCR spectra obtained from the three Si epilayers grown with different bias. Within the experimental errors, the ODCR spectra from the samples grown with the zero and positive bias exhibit similarly a broad CR signal peaking at $B > 500$ G, indicating that all these PL emissions originate from the spatial region where the band structure is similar and undistorted. A slight difference in the peak positions between the two samples is due to a different orientation of the magnetic field with respect to the crystalline axes. The ODCR spectra from the samples grown with the negative bias, on the other hand, can only be observed by monitoring the high-energy PL emissions (0.87–1.03 eV). The fact that the CR signal peaks at $B < 500$ G in these samples gives a strong indication that corresponding emission originates from the strongly disturbed areas where the band structure is not well defined. The reasons why the deeper PL emissions show no noticeable ODCR signal can be manifold, including a much lower carrier mobility or a weaker hot-carrier effect on the carrier recombination. The former case implies that the deeper PL emissions originate from a different spatial region from that of the shallower PL emissions. The sharp line at about 3300 G in Fig. 4 corresponds to an optically detected magnetic resonance signal related to nonradiative defects in the samples,[21] which will not be discussed in this paper.

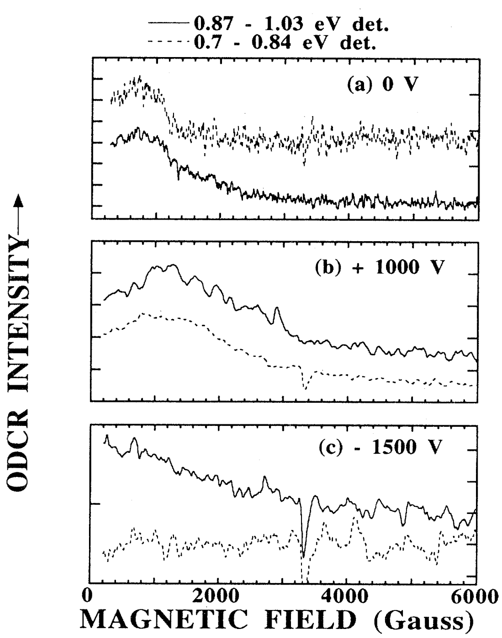

FIG. 4. ODCR spectra monitored in two different spectral ranges from the B-doped samples grown with (a) zero bias, (b) positive bias, and (c) negative bias. The solid and dashed curves were obtained by monitoring the PL emissions in the spectral range 0.87–1.03 and 0.70–0.84 eV, respectively.

IV. DISCUSSION

A. Creation of the BB-related defects

As mentioned above, defects giving rise to deep broad luminescence bands are often reported for Si substrates[10–15] and MBE-grown Si epilayers.[2,16] The presence of such emissions is usually considered as a signature of reduced crystalline quality or purity of the epitaxial film. A strong enhancement of the BB PL observed for the Si films grown with negatively biased substrates gives clear evidence that some defects can be more effectively created by the bombardment of positive ions, presumably Si^+. An additional argument in favor of this conclusion is the previous observations of rather similar PL bands for Si layers after ion implantation[11,12] and reactive-ion etching.[13–15] One could expect that by applying a positive or zero bias and, thus, eliminating the flux of positive ions from bombarding the growth surface, a drastic improvement of the film quality can be achieved. This has in fact been observed in this work by the ODCR experiments that reveal a higher carrier mobility under such growth conditions.

The presence of the 0.78-eV BB's, though weak, even in the samples grown with zero bias indicates that the corresponding defects can readily be introduced as the result of, e.g., low surface adatomic mobility during the low-temperature MBE growth. This observation implies that the formation of the 0.78-eV-related defects is a common process in the low-temperature MBE growth at the present stage. The spectral shape and the properties of this 0.78-eV PL band are the same for the layers grown with positive and zero bias, indicating that the bombardment by negative ions is nearly negligible.

B. Classification of the broad emissions

As is evident from Fig. 1, the photoluminescence bands attributed to the radiation damage of the epitaxial films during the MBE growth are rather broad and have no pronounced spectroscopic structure. In Sec. III we have shown that the ordinary PL spectrum is composed of a number of PL bands originating from different radiative defects. That complicates the analysis of the measured PL spectra, leading in part to the appearance of contradictory models for the nature of the corresponding defects. Based on the results obtained in this work, the BB-related defects can be classified as follows.

1. Two types of defects responsible for the 0.70–0.84 eV PL bands

One of these radiative centers giving rise to the PL band peaking at 0.78 eV is observed in the less-damaged epitaxial films grown with zero or positive bias and can be completely deactivated by the hydrogen treatment [Figs. 1(a) and 1(b)]. With an increase of the external magnetic field, a gradual decrease of the PL intensity is detected [Figs. 3(a) and 3(b)]. According to the ODCR results [Figs. 4(a) and 4(b)] the emission originates from the undistorted regions of the Si epilayers. Although we cannot determine the exact origin of the PL centers, all the data are consistent with the PL transitions related to the point defects or complexes created because of the low growth temperature.

The other type of defect gives rise to the unresolved tail in the PL spectra in this energy range in highly damaged Si films grown with negative bias [Fig. 1(c) and Fig. 2]. The defects related to this PL band cannot be passivated by the hydrogen treatments. The monotonous increase of the PL intensity monitored with an increasing magnetic field [Fig. 3(c)] suggests[25,26] an excitonic origin of the radiative transitions. The PL appearance is observed for the Si films grown with negative bias and correlates with the XRD results, indicating the existence of lattice strain under these growth conditions. The conclusion about the high lattice damage during such growth conditions is further confirmed by the ODCR measurements, which reveal a perturbed band structure. The PL observed could thus be attributed to the excitonic transitions in distorted areas of the structures.

2. Two types of PL centers responsible for the 0.87–1.03 eV PL bands

The PL transitions in the spectral range 0.87–1.03 eV dominate in the PL spectra of the highly damaged Si epilayers grown with negative bias [Fig. 1(c)]. A background PL in the same spectral range can also be observed in the layers grown with zero and positive bias. Both types of the emissions are insensitive to hydrogen passivation. The ODCR measurements show strong lattice distortion for the samples grown with negative bias, whereas for the structures grown with zero or positive bias emission occurs within the undistorted areas. This indicates that different PL centers could be involved in the recombination process.

So far no definite conclusion can be drawn on the chemical identity and geometric structure of these radiative defects. There are, however, indications that the boron dopants are either directly involved in the defect structures or they at least participate in the formation of

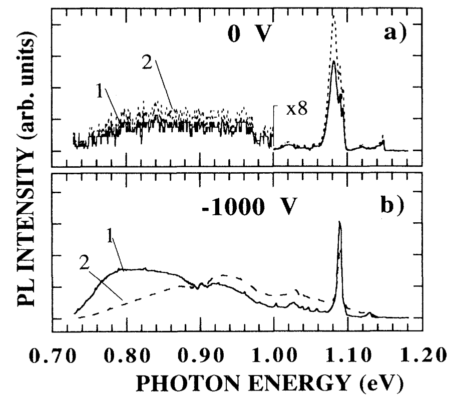

FIG. 5. Photoluminescence spectra of the undoped reference Si epilayers grown with different bias applied to the substrate: (a) zero bias and (b) negative bias at −1000 V. Spectra of the as-grown and the hydrogen-treated samples are shown by the solid and the dashed curves, respectively. The dip around 0.90 eV appearing in all spectra corresponds to the absorption by the water vapor.

these defects. This is partly reflected by markedly different PL bands (Fig. 5) observed in undoped reference samples grown under similar conditions but without the B doping, as compared to those from the samples with the B doping studied in this work (Fig. 1).

V. SUMMARY

We have carried out a detailed study on the broad PL bands in *p*-type modulation-doped Si epilayers grown by MBE with different bias applied to the substrate. Various PL perturbation spectroscopies as well as postgrowth treatments have been performed in order to elucidate the nature of the recombination processes and the responsible defects. Below we summarize the main conclusions drawn from this work:

(i) The creation of BB-related defects is up to now a frequent feature for the MBE-grown Si thin films, and it is probably induced by a low surface adatomic mobility during the low-temperature MBE growth and more significantly by positive-ion bombardment during the growth. (ii) The BB emissions observed in the Si epilayers originate from at least four types of radiative defects, differing by their susceptibility to hydrogen passivation and the PL behavior in a magnetic field or under the CR conditions. (iii) Boron atoms are likely to be directly involved in the defect structures or they at least play an active role in the formation of these defects.

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*On leave from the Institute of the Semiconductor Physics, Ukrainian Academy of Sciences, Kiev, Ukraine.

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