Interface defects and their roles in light-induced phenomena in *a*-Si:H/*a*-$Si_{1-x}N_x$:H multilayers

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The interface defects in the *a*-Si:H/*a*-$Si_{1-x}N_x$:H multilayer have been examined from photoluminescence (PL) and optically detected magnetic resonance (ODMR) measurements, particularly for *a*-Si:H/*a*-$Si_{0.6}N_{0.4}$:H multilayers fabricated by varying the interrupting interval of alternating two gases, i.e., SiH_4 diluted to 10% in H_2 and a mixture gas of SiH_4 (10% in H_2) and pure NH_3. The results of the PL and ODMR measurements are discussed in terms of three kinds of interface defects, i.e., silicon dangling bonds, $T_3{}^0$, separate $T_3{}^+$-$N_2{}^-$ pair defects (*E* centers), and close $T_3{}^+$-$N_2{}^-$ pair defects (E^* centers), where $T_3{}^+$ and $N_2{}^-$ designate the positively charged threefold-coordinated silicon atom and negatively charged twofold-coordinated nitrogen atom, respectively. The light-induced effect on PL and ODMR was also discussed in terms of creation of the interface defects by prolonged illumination. These investigations allow us to elucidate the nature of the interface defects in those multilayers. [S0163-1829(97)04204-5]

I. INTRODUCTION

The multilayer films consisting of *a*-Si:H as a well layer and *a*-$Si_{1-x}N_x$:H as a barrier layer are one of the artificial semiconducting films receiving much attention from the viewpoint of the quantum-size effect. This issue was discussed in a previous paper[1] and also in more detail in a separate paper[2] on the basis of measurements of photoluminescence (PL) and optically detected magnetic resonance (ODMR) in *a*-Si:H/*a*-Si_3N_4:H multilayers. One of the shortcomings of this material is that it contains defects created in its interface region. Such interface defects have been examined by means of electron spin resonance[3,4] (ESR) and photothermal deflection spectroscopy (PDS).[5]

We fabricated multilayer films by varying the interval time for deposition of each layer, t_I, in *a*-Si:H/*a*-$Si_{0.6}N_{0.4}$:H multilayers and optimized t_I to prepare *a*-Si:H/*a*-$Si_{0.6}N_{0.4}$:H multilayers containing less defective interfaces. We also prepared *a*-Si:H/*a*-Si_3N_4:H multilayers at an optimized condition. In a previous paper,[2] we discussed all aspects of PL and ODMR properties of *a*-Si:H/*a*-Si_3N_4:H multilayer films in terms of the quantum-size effect. In those multilayer films, the interface defects also play an important role in their PL and ODMR properties, particularly in the multilayer films with thin well layers. In this paper, we examine the interface effects on the PL and ODMR properties for specially prepared films to enhance the creation of interface effects as mentioned above and also for light-soaked multilayer films in which interface defects are created together with bulk defects. We present the results of PL and ODMR measurements as a function of t_I and those of light-induced effects on PL and ODMR for such multilayer films. These measurements serve to consider the interface defects in the multilayer films and lead us to reach some conclusions about the role of interface defects in recombination processes.

II. EXPERIMENT

a-Si:H/*a*-SiN:H multilayers were prepared by using the rf glow discharge decomposition of two types of gas mixtures. During the interval between deposition of each layer, the system was evacuated and hence the rf plasma was interrupted. Therefore, this interval time t_I becomes one of the very important factors in making a clear interface. We will discuss the effect of t_I on interface defects later. Sample preparation techniques have already been described in more detail in our previous paper.[6] The characteristics of the samples used in this study are listed in Table I.

PL experiments were carried out at 2–400 K, using an unfocused Ar ion laser light of 2.41 eV (514.5 nm) and/or 2.54 eV (488 nm) and 0.2–500 mW (0.8–2000 mW/cm^2) for excitation chopped at about 80 Hz. The light intensity I_{ex} of 500 mW was used for the light soaking. ODMR measurements were carried out at 2 K. The detection system for PL measurements and the ODMR measurements were described in detail in Ref. 7.

III. RESULTS AND DISCUSSION

In the following, we present the results of PL and ODMR measurements and discuss them in terms of three kinds of defects, i.e., silicon dangling bonds, $T_3{}^0$, separate $T_3{}^+$-$N_2{}^-$ pair defects (*E* centers), and close $T_3{}^+$-$N_2{}^-$ pair defects (E^* centers), where $T_3{}^+$, $T_3{}^-$, and $N_2{}^-$ designate positively and negatively charged threefold-coordinated silicon and negatively charged twofold-coordinated nitrogen, respectively. We pay particular attention to those defects created in the interface region. However, these defects have also been either observed or suggested from the ODMR measurements in bulk films of *a*-$Si_{1-x}N_x$:H. Thus it is difficult to separate the defects into those originated from the interface and the bulk. So, samples were prepared by varying the interrupting interval of two alternating gases to enhance the

TABLE I. Characteristics of samples. L_W, well-layer thickness; L_B, barrier-layer thickness; t_I, interval time.

Sample	L_W (Å)	L_B (Å)	Number of periods	t_I (s)	Optical gap (eV)
			a-Si:H/a-$Si_{0.6}N_{0.4}$:H multilayers		
5005	20	40	205	1	1.90
5009	20	40	420	5	1.93
5010	20	40	420	10	1.94
5012	20	40	200	60	1.95
			a-Si:H/a-Si_3N_4:H multilayers		
5103	6	25	350	5	2.36
5107	6	75	150	5	
5109	12	25	300	5	2.09
5104	18	25	250	5	2.00
5106	18	75	135	5	
5105	36	25	150	5	1.85
5112	72	25	100	5	
5121	210	25	36	5	
			a-Si:H		
1502	8400				≈1.80
			a-$Si_{0.6}N_{0.4}$:H		
2504	9000				2.40

creation of interface defects. Interface defects were also created by prolonged illumination. These procedures serve to highlight the interface defects affecting the PL and ODMR properties.

A. Effect of interrupting interval of alternating two gases on interface defects

Amorphous multilayers are prepared by alternating two gases in our deposition system, as described above. Therefore, in order to achieve a sharp interface between each layer, it is necessary that samples are fabricated using the longer interrupting interval of the rf plasma, t_I. In this section, the effect of t_I on interface properties is examined by PL and ODMR measurements before and after light illumination. As reported in our previous paper,[7] we have observed enhancing $(\Delta I)_{ESR}$ and quenching $(-\Delta I)_{ESR}$ signals in ODMR measurements. The intensity of the ODMR signal is proportional to a change in the PL intensity at resonance, ΔI. The quantity of ΔI devided by the PL intensity I is used to characterize the spectral dependence of the ODMR signal, thus canceling the spectral dependence of the detection system.

Figures 1(a) and 1(b) show PL spectra and spectral dependences of ODMR signals taken before (solid curves) and after (broken curves) illumination (I_{ex}=500 mW of 514.5-nm light, 30 min) in a-Si:H and multilayers prepared with various t_I. Two emission bands, i.e., the low-energy band (LEL) and the high-energy band (HEL) can be observed, peaked at about 0.9 and 1.4 eV, respectively. HEL has been attributed to the radiative recombination of trapped electrons in the conduction-band tail with ether trapped holes in the A centers (self-trapped holes in the valence-band tail) for the well layer thickness L_W>10 Å or trapped holes in the

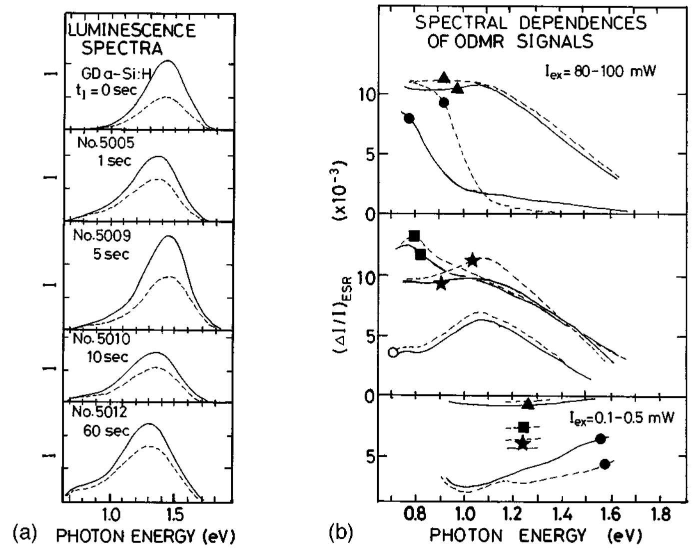

FIG. 1. (a) PL spectra and (b) spectral dependences of enhancing and quenching signals in a-Si:H prepared at 270 °C and a-Si:H/a-$Si_{0.6}N_{0.4}$:H multilayers prepared with various t_I. Solid curves and broken curves show the results before illumination and after illumination (500 mW intensity) of 30 min, respectively. Symbols on the curves represent an a-Si:H film for solid circle and multilayer films prepared with different t_I; triangle: t_I=1 s, square: t_I=5 s, star: t_I=10 s, and open circle: t_I=60 s. Each value in the ordinates is plotted in arbitrary units.

valence-band tail for $L_W \leqslant 10$ Å.[8] LEL has been identified as due to radiative recombination of trapped electrons in defects with trapped holes mentioned above. We characterize HEL as the PL peak energy, E_p, the width at half maximum, ΔE, and the PL intensity at E_p,I_p. These values are plotted as functions of t_I in Fig. 2. E_p and I_p rapidly increase and show a maximum and then decrease with increasing t_I from t_I=1 s. ΔE shows a minimum at t_I=5 s. Both the increase of E_p and the decrease of ΔE are closely correlated with the decrease of the width of band-tail states. The decrease of I_p is indirectly related to the increase in the number of nonradiative recombination centers in the gap. As the rf plasma is not interrupted in alternating two gases in the case of t_1=1 s, the alloying effects occur. Therefore, t_I=5 s is used

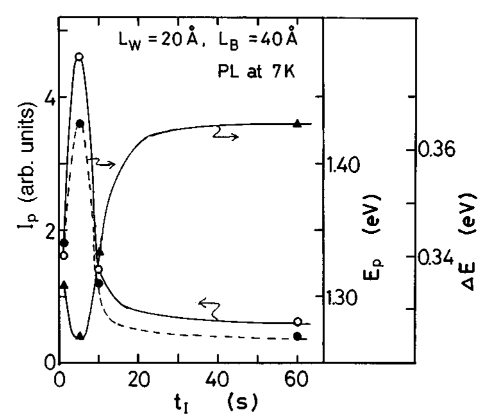

FIG. 2. Plots of PL peak energy, E_p (solid circle), the width at half maximum, ΔE (solid triangle), and PL intensity at E_p, I_p (open circle), as a function of t_I.

in order to prepare the less defective multilayers in our deposition system. As reported previously, the values of I_p of a-Si:H films containing 400 homo-interfaces by switching the plasma on and off with $t_I=5$ and 30 s are almost the same as that of an a-Si:H film deposited continuously without interfaces.[9] These values are large and independent of t_I within our experimental conditions, compared with those of multilayers. In such films, LEL cannot be clearly observed at 7 K, compared with that for multilayers. These results indicate that LEL is strongly correlated with defects created at the heterointerface between a-Si:H and a-$Si_{1-x}N_x$:H and that chemical and physical conditions of the surface of the deposited film that acts as a substrate for the next layer depend on t_I in the case of the creation of the interface between the a-Si:H well layer and the a-$Si_{1-x}N_x$:H barrier layer. Further details of the effect of t_I for PL properties have been discussed in a previous paper.[6]

Next, we describe the results of ODMR measurements. The resonance at the A center enhances PL intensity I. The magnitude of $(\Delta I/I)_{ESR}$ at the A center increases with decreasing the PL photon energy in a-Si:H before illumination, as shown in Fig. 1(b). Therefore, it is considered that the observed enhancing signal in multilayers [see Fig. 1(b)] is composed of two enhancing signals, i.e., the A center and E center resonances peaked at the photon energy $h\nu\approx0.8$ and 1.08 eV, the A and E spectra, respectively. The enhancing signal in a multilayer with $t_I=60$ s (open circle) is mainly composed of the E spectrum. However, the A spectrum is mainly seen in a multilayer with $t_I=5$ s (square). This shows that the characters of the well-layer material, a-Si:H, are kept in a multilayer prepared using $t_I=5$ s. The value of $(\Delta I/I)_{ESR}$ of the enhancing signal increases after illumination over the whole $h\nu$. This is due to the light-induced radiative center whose spectrum is peaked at $h\nu\approx1.08$ eV, as clearly shown in the figure. Therefore, it is considered that the nature of interface defects before illumination is similar to that of the defects created by illumination. The value of $(-\Delta I/I)_{ESR}$ of the quenching signal after illumination becomes slightly smaller or indicates almost the same value as that before illumination. However, the PL intensity decreases after illumination in the whole $h\nu$ in multilayers. Therefore, we need to introduce another new nonradiative center in addition to the Si dangling bond, Si db, which acts as the nonradiative center, in order to interpret the above results. We name it the E^* center. When considering PL spectrum and the spectral dependence of ODMR signals, the defect-related PL is clearly correlated with the radiative E center, which changes easily to the nonradiative E^* center with increasing the number of Si db's in the presence of a large amount of nitrogen and hydrogen atoms. It is suggested that the existence of hydrogen atoms in the network of the lattice is closely associated with the lattice distortion, especially under and after illumination. The nature of the E and E^* centers is discussed in the next section.

B. Effect of L_W dependence on interface defects

1. *Spectral dependence of* ODMR *signals*

Figures 3(a) and 3(b) show the PL spectra taken before (solid curves) and after (broken curves) illumination ($I_{ex}=500$ mW of 514.5- or 488-nm light, 30 min) and the

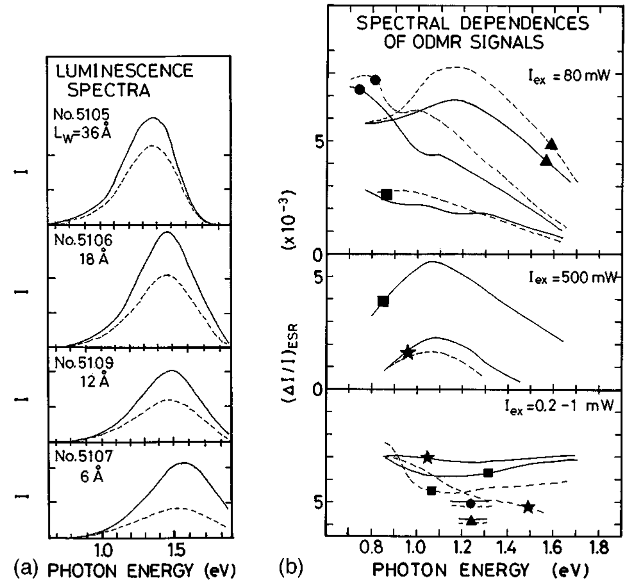

FIG. 3. (a) PL spectra and (b) spectral dependences of enhancing and quenching signals in a-Si:H/a-Si_3N_4:H multilayers prepared with various L_W. Solid curves and broken curves show the results before illumination and after illumination (500 mW intensity) of 30 min, respectively. Symbols on the curves represent multilayer films prepared with different L_W; circle: $L_W=36$ Å, triangle: $L_W=18$ Å, square: $L_W=12$ Å, and star: $L_W=6$ Å. Each value in the ordinate is plotted in arbitrary units.

ODMR signals in a-Si:H films and a-Si:H/a-Si_3N_4:H multilayers with $L_W=36$, 18, 12, and 6 Å, respectively. First, we summarize the results observed in a-Si:H. The ratio of PL intensity after illumination to that before illumination, I_f, in the low-energy region around $h\nu=0.8$ eV increased by a factor more than 2. As mentioned before, the resonance at the A center enhances I. The magnitude of $(\Delta I/I)_{ESR}$ at the A center resonance increases with decreasing the photon energy. The values of $(\Delta I/I)_{ESR}$ of the enhancing signal taken after illumination become small in high-energy luminescence and increase around $h\nu=0.9$ eV, compared with those taken before illumination, while I_f becomes large in the low-energy region. These phenomena are associated with the creation of the new radiative recombination center in the gap region; i.e., the spectrum of $(\Delta I/I)_{ESR}$ of the enhancing signal after illumination can be regarded as the superposition of each spectrum of the A center and the newly created radiative center named E center, although the E center has not been identified in a-Si:H. In multilayers, we have observed two peaks around 0.75–0.9 and 1.1–1.2 eV in the spectral dependences of the enhancing signal, $(\Delta I/I)_{ESR}$, and called A and E spectra, respectively. The A spectrum due to the self-trapped hole (A center) has been observed in a-Si:H films before illumination, as described above. The E spectrum due to a trapped electron at a ${T_3}^+$-${N_2}^-$ pair defect (E centers) has been observed in a-$Si_{1-x}N_x$:H films.[10] The spectrum of $(\Delta I/I)_{ESR}$ in multilayers with $L_W=36$, 18, and 12 Å consists of the A and E spectra when I_{ex} of Ar^+ laser light is less than 100 mW. When I_{ex} is 500 mW, the E spectrum is clearly observed in multilayers with $L_W=12$ and 6 Å with a g value ($g=2.0045$–2.0046) whose spectral dependences are different from that of the A center, as shown in

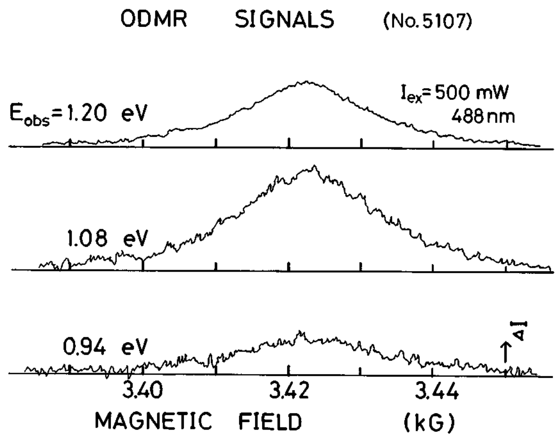

FIG. 4. Enhancing signals observed at $h\nu = 1.20$, 1.08, and 0.94 eV, i.e., $E_{obs} = 1.20$, 1.08, and 0.94 eV, for a-Si:H/a-Si_3N_4:H multilayers with $L_W = 6$ Å, using $I_{ex} = 500$ mW.

Fig. 4. We have not observed the anisotropy in the E center. After prolonged illumination, $(\Delta I/I)_{ESR}$ in multilayers with $L_W = 36$, 18, and 12 Å increased as shown in Fig. 3(b), while $(\Delta I/I)_{ESR}$ in multilayers with $L_W = 6$ Å decreased. This suggests the creation of both radiative and nonradiative centers in the interface region. These centers are considered to consist of the same kind of defects and whether they become the radiative or nonradiative centers depends upon the distance between each defect, as discussed below.

The quenching signal, $(-\Delta I/I)_{ESR}$, due to Si db's is observed under a weak I_{ex}. After illumination, the Si db signal is enhanced in a-Si:H films and multilayers with $L_W = 12$ and 6 Å, but its value is almost the same in those with $L_W = 36$ and 18 Å.

These observations are interpreted in terms of a defect model described above as follows: As was previously discussed, when both a-Si:H and a-SiN:H layers come in contact with each other, electrons flow from the a-SiN:H layer into the a-Si:H layer because of the difference of the Fermi level of each layer material.[11] As a result, some of the Si db, $T_3{}^0$, in the a-Si:H layer becomes $T_3{}^-$ (positive U), while some of the Si db in the a-Si:H layer becomes $T_3{}^+$ (positive U). Thus, as the twofold-coordinated nitrogen, $N_2{}^0$, seems to be present in the a-SiN:H layer, the coupled pairs $T_3{}^+$-$N_2{}^-$ are considered to be formed in the interface region, especially the barrier layer side. When $T_3{}^+$ and $N_2{}^-$ are separated from each other, this pair defect (E center) contributes to LEL and to the enhancing signal, while close $T_3{}^+$-$N_2{}^-$ pairs (E^* centers) seem to us to contribute to nonradiative recombination in a similar way to the case of a-$Si_{1-x}N_x$:H.[10] During prolonged illumination, light is almost absorbed in the a-Si:H layer because of the large optical gap of a-Si_3N_4:H film, and the light-induced Si db is created in the a-Si:H layer. As a result, the neutral Si db becomes $T_3{}^-$ in the a-Si:H layer, while $T_3{}^+$ is formed in the a-SiN:H layer. Therefore, the number of separate $T_3{}^+$-$N_2{}^-$ pairs increases in the a-SiN:H layer near the interface. This produces the increase in $(\Delta I/I)_{ESR}$ of the enhancing signal in multilayers with $L_W = 36$–12 Å after illumination. Although the value of $(-\Delta I/I)_{ESR}$ of the quenching signal before and after illumination in multilayers with $L_W = 36$–18 Å are almost the same, the intensity of HEL decreases after illumination. This indicates that after illumination another nonradiative recombination path being due to the E^* centers near the interface occurs along with Si db's. $(-\Delta I/I)_{ESR}$ of the quenching signal in a multilayer with $L_W = 6$ Å increased after illumination. This result is accounted for in the following way: As has already been reported, the self-trapping of holes seems not to occur for multilayers with $L_W = 6$ Å. According to a model for light-induced creation of Si db's,[12] self-trapping of holes in specific weak Si-Si bonds plays an important role in light-induced creation of Si db's in a-Si:H, so that Si db's may not be created by prolonged illumination for multilayers with $L_W = 6$ Å because of the change from self-trapped holes to trapped holes in the valence-band tail with decreasing L_W less than $L_W = 10$ Å. After prolonged illumination at 2 K, however, some of the trapped electrons at $T_3{}^+$ (positive U) and trapped holes at $T_3{}^-$ (positive U) appear to remain stable, because the temperature is kept at 2 K after illumination and electron-hole recombination at Si db's is suppressed for this multilayer owing to its two-dimensional nature. Such a stable Si db ($T_3{}^0$) contributes to the quenching signal whose intensity increases by prolonged illumination, as shown in Fig. 3(b).

2. Excitation intensity dependence of ODMR signals

The ODMR signal intensities in multilayers with $L_W = 36$, 12, and 6 Å are shown as a function of I_{ex} in Figs. 5(a)–5(c), respectively. Before illumination, with increasing I_{ex}.$(\Delta I/I)_{ESR}$ of the enhancing signal at $g \approx 2.0$ increases and tends to saturate at strong I_{ex} in the multilayer with $L_W = 36$ Å (No. 5105). However, we could observe the enhancing signal only when we used $I_{ex} = 500$ mW in multilayers with $L_W = 12$ and 6 Å (No. 5109 and No. 5103) and the values of $(\Delta I/I)_{ESR}$ of the enhancing signal at $I_{ex} = 500$ mW are small, compared with those in a-Si:H and multilayers with thick L_W. From the point of view of a rate equation model of ODMR signals,[7] it is suggested that these different behaviors in the enhancing signal between multilayers with thick L_W such as $L_W = 36$ Å and thin L_W such as $L_W = 12$ and 6 Å are due to the difference of the radiative recombination rate. Therefore, these can be attributed to two radiative recombination centers with different natures, i.e, the A and E centers, respectively, as also suggested from the results of the spectral dependence of ODMR signals.

The $(-\Delta I/I)_{ESR}$ of the quenching signal at $g \approx 2.0$ exhibits a plateau with a limiting value at weak I_{ex} and then decreases with increasing I_{ex}. The values of $(-\Delta I/I)_{ESR}$ in multilayers with $L_W = 36$–6 Å are almost the same and are $(5-7) \times 10^{-3}$, while those are increased in a-$Si_{1-x}N_x$:H films with increasing the N content;[10] i.e., the values of $(-\Delta I/I)_{ESR}$ before illumination are 4×10^{-3} to 1×10^{-2} in the films with $x = 0$ to 28 at %, respectively. The increase of the values with N content can be attributed to the increase in the number of Si db's. The result of the magnitude of $(-\Delta I/I)_{ESR}$ being almost independent of L_W may be due to the fact that the nonradiative recombination rate is not proportional to N_s, but to $N_s L_W$, because its two-dimensional nature is dominated particularly for multilayers with L_W of less than 30 Å.[2]

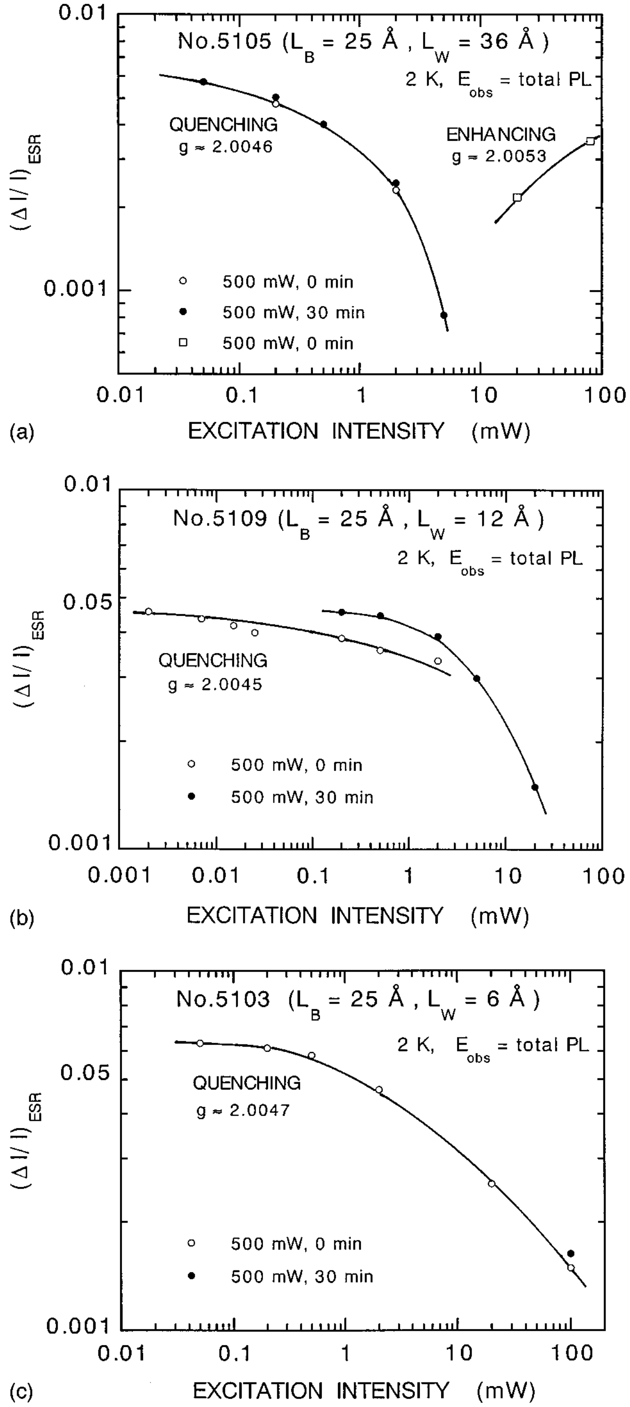

FIG. 5. ODMR signal intensities, $(\Delta I/I)_{\mathrm{ESR}}$, taken before and after illumination (500 mW intensity) as functions of excitation intensity in a-Si:H/a-Si_3N_4:H multilayers with (a) $L_W=36$ Å, (b) $L_W=12$ Å, and (c) $L_W=6$ Å. E_{obs} is total PL.

We have observed another quenching signal at $g\approx 4.0$ in multilayers, which is attributed to the triplet exciton resonance.[13] Its details will be reported elsewhere.

3. Photoluminescence fatigue caused by prolonged illumination

We have observed the light-induced PL fatigue in multilayers. The ratio of I_p after illumination (500 mW, 30 min) to I_p before illumination, F_R, is shown as a function of

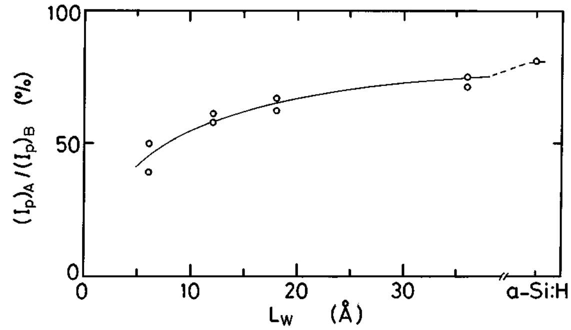

FIG. 6. Plot of the ratio of PL intensity at E_p after illumination, $(I_p)_A$, to that before illumination, $(I_p)_B$, as a function of L_W.

L_W in Fig. 6, where the ratio obtained in the a-Si:H sample 1502 is also shown for comparison. This value of 80% is larger than that shown in Fig. 1(a) where the a-Si:H sample prepared at different conditions is used. This difference comes from different experimental conditions for PL fatigue and also from different quality of the film, i.e., particularly hydrogen content and Si db density. The experimental condition for PL fatigue on sample 1502 was the same as those for the multilayer films used for this experiment. The result that the value of F_R decreases with decreasing L_W as shown in Fig. 6 is considered in terms of the model described above as follows: The PL fatigue occurs as a result of an enhancement of nonradiative recombination due to light-induced creation of Si db's, i.e., principally neutral Si db and partially E^* centers. We consider mainly neutral Si db's as nonradiative centers. We take a bond-breaking model,[12,14,15] in which a weak Si-Si bond adjacent to a Si-H bond is broken through nonradiative recombination of an electron with a self-trapped hole in this weak Si-Si bond and then two Si db's are separated through the Si-H bond switching and hopping and/or tunneling of hydrogen coupled with further weak-bond breaking. Thus, self-trapping of holes becomes one of the important key processes for the PL fatigue. For multilayers, the ODMR measurement suggests that self-trapping of holes hardly occurs for $L_W<10$ Å. This means that PL fatigue does not occur for multilayers with $L_W=6$ Å. This is obviously inconsistent with the result that the PL fatigue is enhanced for this film compared to those with thicker L_W, as seen in Fig. 6. Hence, for this film, another mechanism seems to operate for light-induced creation of Si db's. Capture of electrons and holes created under illumination by positive-U, T_3^+ and T_3^- centers, respectively, results in creation of neutral Si db's being stable at low temperatures such as 2 K even after illumination is turned off. It should be noted that illumination was done at 2 K. This is consistent with the observation that the quenching ODMR signal intensity, $(-\Delta I/I)_{\mathrm{ESR}}$, greatly increased after prolonged illumination at 2 K for this film compared to those with $L_W=12$–36 Å. Charged Si db's are thought to be more dominantly created in multilayers with thin L_W, i.e., multilayers containing a number of interfaces. In the bond-breaking model, the nonradiative recombination rate at weak Si-Si bonds is also one of the important key factors for light-induced creation of Si db's. For multilayers with thin L_W, two-dimensional character is enhanced for recombination processes, as has been mentioned in our previous papers.[1,2]

This results in a decrease in the recombination rate. However, when the well-layer thickness becomes small, the electron-hole confinement effect is enhanced and this results in an increase in the recombination rate. Thus, the above two effects compete with each other. The experimental result shown in Fig. 6 suggests that the latter effect predominates over the former one within the framework of the bond-breaking model. The electron-hole confinement effect also enhances the capture rate of electrons and holes by the T_3^+ and T_3^- centers, which is essential for light-induced creation of neutral dangling bonds for a multilayer with $L_W = 6$ Å.

In the following, we consider light-induced effects on the quenching ODMR signal due to neutral dangling bonds and the enhancing ODMR signals. As mentioned above, the quenching signal intensity, $(-\Delta I/I)_{\mathrm{ESR}}$, greatly increases after prolonged illumination for a multilayer with $L_W = 6$ Å. On the other hand, its increase for a multilayer with $L_W = 12$ Å is small, and it is not so much increased for those with $L_W = 18$ and 36 Å as seen in those with $L_W = 6$ and 12 Å. This is related to the weakness of the electron-hole confinement effect with increasing L_W and also to creation of E and E^* centers by illumination. Even for multilayers with $L_W = 18$ and 36 Å, we can see the PL fatigue, as shown in Fig. 6. This seems inconsistent with the behavior of the quenching signal as mentioned above, but it should be pointed out that the PL fatigue also occurs by nonradiative recombination at E^* centers. So, the situation of the PL fatigue is rather complicated compared to a-Si:H bulk films. The above discussion is only of qualitative nature. Quantitative discussions are not so easy at present.

In a-Si:H bulk films, the magnitude of $(\Delta I/I)_{\mathrm{ESR}}$ at the enhancing signal increases at the low photon energy region after prolonged illumination, as shown in Fig. 1. This is associated with enhancement of the low-energy PL by prolonged illumination.[16] In contrast with this result, the enhancing signal increases particularly around 1.1 eV in a-Si:H/a-Si_3N_4:H multilayers with L_W of less than 30 Å, as shown in Fig. 3(b). This may be due to creation of E centers by prolonged illumination, as mentioned above.

IV. CONCLUSIONS

In this paper, three kinds of interface defects, i.e., Si db's, separate T_3^+-N_2^- pair defects (E centers), and close T_3^+-N_2^- pair defects (E^* centers) are considered in the correlation of PL and ODMR properties of a-Si:H/a-SiN:H multilayers. The effect of interrupting the interval of alternating two gases on their PL and ODMR properties is examined. Creation of interface defects by prolonged illumination is observed, which also affects the PL and ODMR properties. From these investigations, it is concluded that the interface defects play an important role in PL and ODMR of a-Si:H/a-SiN:H multilayers.

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