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Comparison of epitaxial thin layer GaN and InP passivations on InGaAs/GaAs near-surface quantum wells

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The optical properties of the *in situ* epitaxial GaN and InP passivated InGaAs/GaAs near-surface quantum wells, which were fabricated by metal organic vapor phase epitaxy, are investigated. Low-temperature photoluminescence (PL), time-resolved photoluminescence, and photoreflectance are used to study the passivation effect. Both GaN and InP passivations are observed to significantly enhance the PL intensity and carrier lifetime and to reduce the surface electrical fields. Comparison of the methods shows that the epitaxial InP passivation is more effective. However, epitaxial GaN and nitridation methods are comparable with InP passivation. © 2006 American Institute of Physics. [DOI: 10.1063/1.2208557]

It is known that the optical performance of near-surface GaAs structures is seriously restricted by the high density of surface states, which can pin the Fermi level near the middle of the band gap. Various passivation techniques using different material combinations and processing methods have been intensively investigated to reduce this effect. For instance, surface chemical treatment, epitaxial growth of InP and GaP layers, and surface As–P exchange reactions have been widely utilized for surface passivation.^{1–4} It has been reported that metal organic vapor phase epitaxy (MOVPE) grown ultrathin InP and GaN layers [1 monolayer (ML)] show efficient passivation in AlGaAs/GaAs (Ref. 5) and InGaAs/GaAs (Ref. 6) near-surface quantum wells (QWs) by increasing the photoluminescence (PL) intensity by factors of 4 and 20, respectively. GaN is considered to be a promising material for surface passivation due to its mechanical and chemical stability. Other works have also reported that *in situ* epitaxial surface passivation methods show considerable effect in reducing the surface state density of GaAs compared to other techniques.^{7,8}

In this letter, we study the passivation effect of epitaxially grown one-ML-thick GaN layer on In_{0.25}Ga_{0.75}As/GaAs near-surface QW and compare it with InP passivation. The passivation effects are characterized by low-temperature PL, time-resolved photoluminescence (TRPL), and room temperature photoreflectance (PR) spectroscopy. Both GaN and InP passivations show significant enhancement in the PL intensity and carrier lifetime of the InGaAs/GaAs near-surface QW. PR spectroscopy shows that these epitaxial passivation techniques efficiently reduce the surface electrical fields of GaAs.

All the samples were grown in a horizontal MOVPE reactor at atmospheric pressure using tertiarybutylarsine (TBAs), trimethylgallium (TMGa), trimethylindium (TMIIn), and dimethylhydrazine (DMHy) as precursors for arsenic, gallium, indium, and nitrogen, respectively. A 4-nm-thick In_{0.25}Ga_{0.75}As near-surface QW was sandwiched by a 100 nm buffer layer and a 5 nm top barrier layer of GaAs on a semi-insulating (100) GaAs substrate. A 1-ML-thick InP or

GaN layer was grown on the GaAs top barrier as the passivation layer. In one sample, the passivation was performed using As–N exchange to nitridate the GaAs surface by exposing the sample to DMHy. The QW and InP passivation layer were grown at temperature of 650 °C while the GaN passivation layer and nitridation were fabricated at 550 °C. An unpassivated near-surface QW and an unpassivated deep-QW sample were also studied for reference. We named these samples as I, II, III, IV, and V for convenience, as shown in Table I. More details about the sample preparation and *in situ* InP and GaN passivations by MOVPE have been reported elsewhere.^{5,6,9}

The low-temperature (10 K) continuous-wave photoluminescence (cw-PL) measurements were conducted by utilizing a diode-pumped frequency-doubled Nd:YVO₄ laser emitting at 532 nm for excitation. A liquid-nitrogen-cooled germanium detector and standard lock-in techniques were used to record the PL spectra. The low-temperature TRPL measurements were performed by exciting the samples with 150 fs pulses at 800 nm from a mode locked Ti:sapphire laser and by detecting the signal using a Peltier-cooled microchannel plate multiplier and time-correlated single photon counting electronics. For the room temperature PR measurement, a 488 nm argon ion laser and a halogen lamp were used for modulation and pump light sources, respectively. The PR spectra were recorded by a Si *p-n* detector using standard lock-in techniques. The surface morphology of the samples was scanned by contact-mode atomic force microscopy (AFM).

Figure 1 shows the surface morphology of samples II and IV from 3 × 3 μm² AFM scans with a vertical scale of 5 nm. Smooth sample surfaces and clear atomic layer ter-

TABLE I. Description of the samples.

Sample	Top barrier (nm)	Passivation
I	5	1 ML InP
II	5	1 ML GaN
III	5	Nitridated
IV	5	Unpassivated
V	20	Unpassivated

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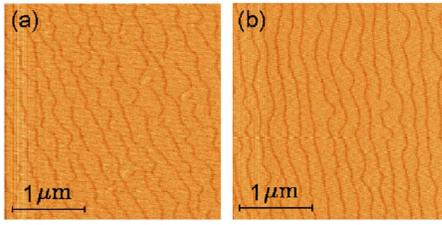


FIG. 1. (Color online) AFM images of (a) GaN passivated and (b) unpassivated samples (samples II and IV). The scan size is $3 \times 3 \mu\text{m}^2$ and vertical scale is 5 nm.

ances can be seen in Figs. 1(a) and 1(b). Scans of the other samples (not shown here) show no obvious differences. This indicates that the passivation process does not degrade the surface morphology of the samples.

The low-temperature cw-PL intensities of the as-grown samples and the same samples after 2 months in air ambient are shown in Fig. 2. The inset shows the PL spectra of the as-grown InP passivated sample (sample I). It can be clearly seen that the PL intensities of all of the passivated samples gain a strong enhancement compared to the unpassivated near-surface QW. For the as-grown samples, the enhancement factor is about 200 for sample I and about 150 for samples II and III. After 2 months of air exposure, the PL intensities of all of the passivated samples were reduced in some extent but are still comparable to the unpassivated deep quantum well (sample V). Compared to the unpassivated near-surface QW, the PL intensity of the InP passivated sample is more than three orders of magnitude larger. This implies that the passivation effect not only reduces the density of surface states but also protects the samples against oxidation while the unpassivated sample degrades severely.

Time-resolved photoluminescence measurements were used to study the carrier dynamics. Figures 3(a) and 3(b) show the low-temperature TRPL transients of the as-grown samples. Carrier lifetime τ was determined by exponential fits $\exp(-t/\tau)$ as indicated in Fig. 3(a) and shown in Table II.

From these results we find that the carrier lifetimes of the passivated samples I, II, and III are longer than those of the unpassivated samples IV and V. After 2 months in air ambient (the TRPL transients not shown here), the unpassi-

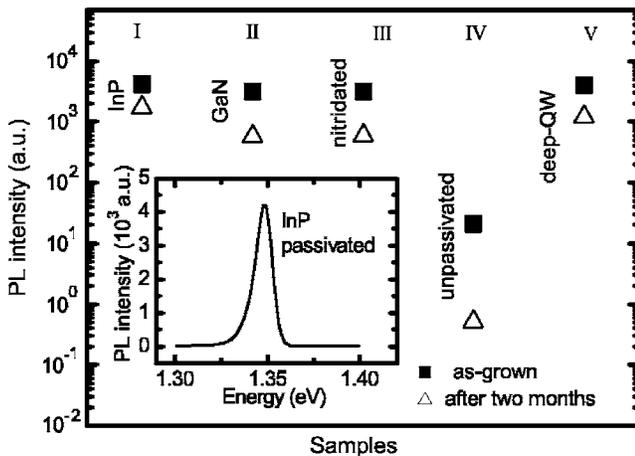


FIG. 2. Low-temperature PL intensities of InP passivated (sample I), GaN passivated (II), nitridated (III), unpassivated near-surface QW (IV), and unpassivated deep-QW (V) samples. The inset shows the PL spectra of as-grown InP passivated (I) sample.

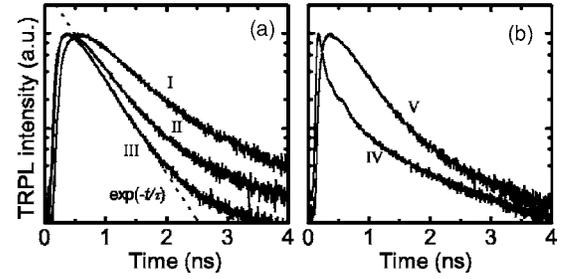


FIG. 3. Low-temperature TRPL transients of (a) InP passivated (sample I), GaN passivated (II), and nitridated (III) and (b) unpassivated (IV) and deep-QW (V) as-grown samples.

ated near-surface QW is degraded severely so that the PL intensity is very low and decay time cannot be confirmed. The passivated samples still show comparable carrier lifetime with the corresponding unpassivated samples. However, the unpassivated deep QW (sample V) shows larger carrier lifetime after long term air exposure. It is assumed to be caused by the inhomogeneity of the sample.

Figure 4 shows the PR spectra of the samples measured at room temperature. An obvious reduction in the periodicity of the Franz-Keldysh oscillations (FKOs) in passivation samples is observed. It can also be observed that the value of modulated reflectance $\Delta R/R$ of InP passivated sample is smaller than in other samples. This is assumed to be caused by the lower density of states in InP passivated sample (sample I). The relationship between the extrema of the FKOs and the surface electrical field can be expressed with^{10,11}

$$m\pi = \phi + \frac{4}{3}[(E_m - E_g)/(\hbar\theta)]^{3/2}, \quad (1)$$

where m is the index of the m th extremum, E_m is the probe photon energy, E_g is the energy band gap, and $\hbar\theta$ is the FKO characteristic energy. It is given by

$$(\hbar\theta)^3 = (q^2\hbar^2 F^2)/(2\mu), \quad (2)$$

where F is the surface electric field, q is the magnitude of the electronic charge, and μ is the reduced mass using the effective mass of the electron and the heavy hole in GaAs ($\mu = 0.056m_0$).¹¹ Based on the equations above, the quantity of $(4/3\pi)(E_m - E_g)^{3/2}$ vs m should yield a straight line with a slope $(\hbar\theta)^{3/2}$, and then the surface electrical field can be calculated.

Figure 5 shows the value of $(4/3\pi)(E_m - E_g)^{3/2}$ as a function of the extremum peak index m . The inset shows the extremum peak indices of a PR spectrum. The calculated values of the electrical field are also shown in Fig. 5. It has been reported that the electrical fields of phosphor and sulfur passivated samples were 25.8 and 39.1 kV/cm compared to the 45.7 kV/cm in unpassivated sample.³ In this study the values of the electrical field are 23.7, 34.8, and 42.9 kV/cm in InP passivated, GaN passivated, and unpassivated

TABLE II. The carrier lifetime τ of samples (* after 2 months of air exposure).

Sample	I	II	III	IV	V
τ (ns)	0.90	0.67	0.56	0.17	0.55
τ^* (ns)	0.79	0.68	0.52	...	0.90

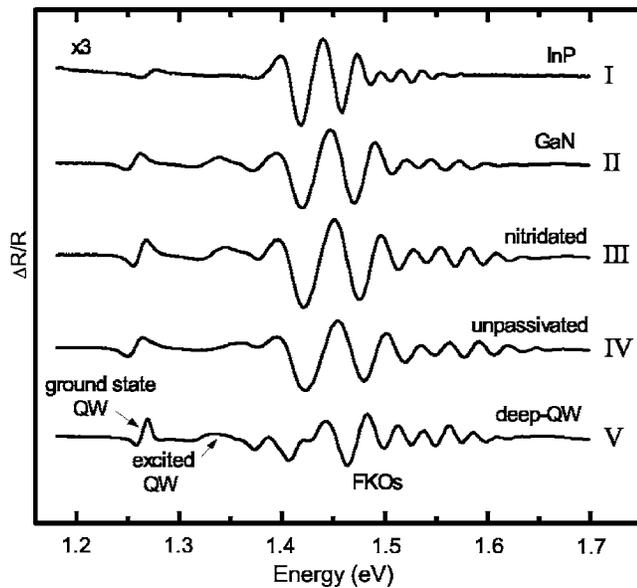


FIG. 4. Room temperature PR spectra of InP passivated (sample I), GaN passivated (II), nitridated (III), unpassivated near-surface QW (IV), and unpassivated deep-QW (V) samples.

samples, respectively. As in the case of cw-PL measurements, the InP layer seems to be more effective in the passivation of GaAs surface than the GaN layer.

In summary, passivation effect of epitaxially grown thin GaN and InP layers on InGaAs/GaAs near-surface QW was investigated. Both GaN and InP passivations were observed to significantly enhance the PL intensity and carrier lifetime and to reduce the surface electrical fields. Comparison of the methods showed that the epitaxial InP passivation is more effective. However, epitaxial GaN and nitridation methods were comparable with InP passivation. All in all, the epitaxial *in situ* passivation using thin GaN and InP layers showed a significant effect by improving the PL intensity, extending the carrier lifetime, and reducing the surface electrical field of near-surface InGaAs/GaAs QWs.

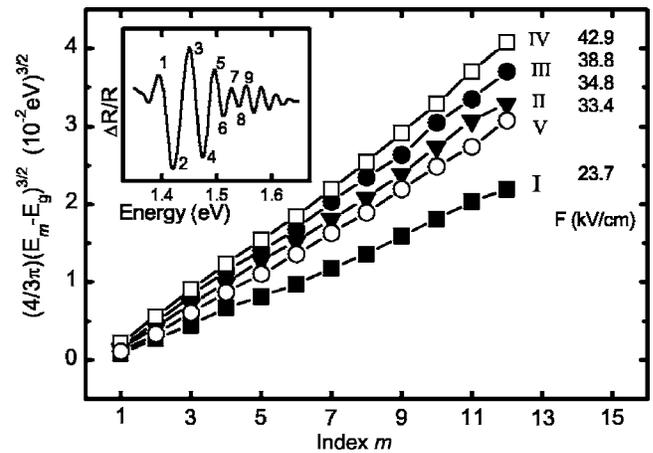


FIG. 5. The value of $(4/3\pi)(E_m - E_g)^{3/2}$ as a function of the extremum peak index m for InP passivated (sample I), GaN passivated (II), nitridated (III), unpassivated near-surface QW (IV), and unpassivated deep-QW (V) samples. The inset shows the extremum peak indices m of a PR spectrum.

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