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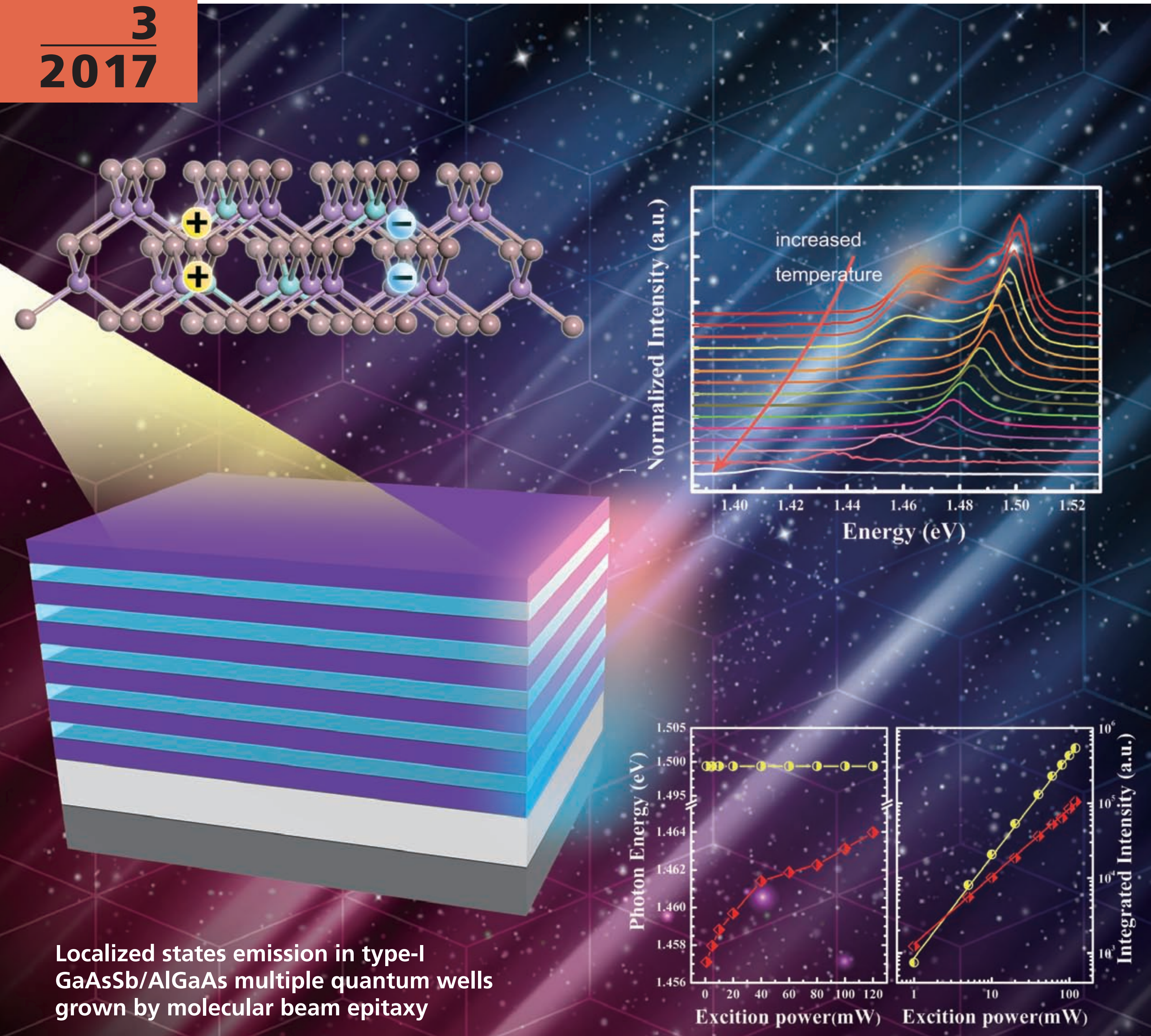

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# Localized states emission in type-I GaAsSb/AlGaAs multiple quantum wells grown by molecular beam epitaxy

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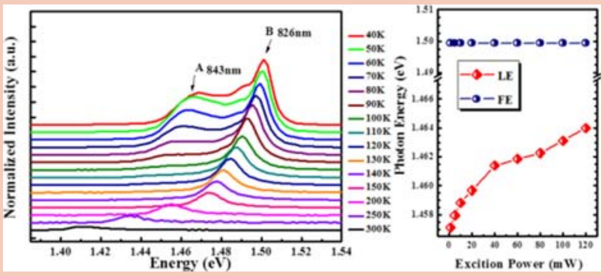
As an important candidate for novel infrared semiconductor lasers, the optical properties of GaAsSb-based multiple quantum wells (MQWs) are crucial. The temperature- and excitation power-dependent photoluminescence (PL) spectra of the $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs, which were grown by molecular beam epitaxy, were investigated and are detailed in this work. Two competitive peaks were observed from 40 K to 90 K. The peak located at the low-energy shoulder was confirmed to be localized states emission (LE) and the high-energy side peak was confirmed to be free-carrier emission by its temperature-dependent emission peak position. It is observed that the LE peak exhibited a blueshift with the increase of laser excitation power, which can be ascribed to the band filling effect of localized states. Our studies have great significance for application of GaAsSb-based MQWs in infrared semiconductor lasers.



**1 Introduction** III–V group semiconductors have received increasing interest owing to their potential applications on optoelectronic devices [1, 2]. The $GaAs_{1-x}Sb_x$ material system is studied for a wide range of optoelectronic applications including quantum well lasers [3], infrared photodetectors [4], and high-performance tunnel field effect transistors (TFET) [5]. GaAsSb materials possess a large lattice bowing parameter and their bandgap is around 0.7–1.42 eV, which is located in the wavelength range for optical communication [6]. As a result, $GaAs_{1-x}Sb_x$ is considered as one of the candidates for a variety of novel infrared semiconductor lasers [7, 8]. In addition, its wide absorption almost covers the solar spectrum ranges, $GaAs_{1-x}Sb_x$ can also be used for solar cells [9, 10]. Compared to the ternary alloy, $GaAs_{1-x}Sb_x$-based multiple quantum wells (MQWs) possess higher emission efficiency and better tunability of the bandgap [11, 12]. However, the optical properties of $GaAs_{1-x}Sb_x$-based MQWs are not yet fully understood, which greatly limits their applications.

For semiconductor materials, the presence of localized states is a common phenomenon [13–15]. Localized centers can easily trap free carriers that greatly affect their optical properties as well as the carrier dynamics in the material system. There are many reasons that will lead to the formation of localized states in semiconductors, such as the fluctuation of alloy components, the interface roughness, defects, etc. [16].

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These factors can produce the random fluctuation of the potential in semiconductor materials, which can expand the conduction- and valance-band edges and lead to an exponential tail in the density of states. The disorder effects on electronic states of materials can be observed through the broadening of optical spectra. The broadening often manifests as the formation of band tail states in the band-edge region. Many research efforts have been carried out and it has been found that the localized states in InGaN or GaAsSbN systems have a strong effect on carrier motion, and that the radiative recombination is generally dominated by localized states at low temperatures [16–18]. In our previous studies, it is found that localized states exist in low Sb constituent $GaAs_{1-x}Sb_x$ ($x = 0.06, 0.08, 0.09$) alloys [19]. Localized states were studied for type II GaAsSb/GaAs QWs by both photoluminescence and time-resolved photoluminescence [20, 21]. However, there is little research on the GaAsSb/AlGaAs MQWs system. Because of the type-I quantum well structure, AlGaAs barriers lead to a better electron confinement than the GaAs barriers. GaAsSb/AlGaAs QWs have better emission properties than GaAsSb/GaAs QWs. However, the carrier dynamics of localized states in $GaAs_{1-x}Sb_x$-based MQWs is complicated and requires further study.

In this paper, $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs have been grown by molecular beam epitaxy (MBE) and their optical properties and carrier dynamics have been investigated. Temperature- and excitation power- (under continuous wave excitation) dependent photoluminescence (PL) measurements were employed to analyze the localized states characteristics in MQWs. Our studies are of great significance for further device application of $GaAs_{1-x}Sb_x$-based MQWs.

## 2 Experimental

The $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs samples employed in this work were grown on semi-insulating GaAs(100) substrates by using a DCA P600 solid source molecular beam epitaxy system. $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs contains 500 nm GaAs buffer layer, five periods $GaAs_{0.92}Sb_{0.08}$ (7 nm) and $Al_{0.2}Ga_{0.8}As$ (17 nm). The growth temperature of $GaAs_{0.92}Sb_{0.08}$ was 500 °C. All layers were unintentionally doped. The schematic diagram of the $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs structure and the energy band are shown in the inset of Fig. 1.

The optical properties of $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs were investigated by laser spectroscopy. A 655 nm semiconductor laser was used as the excitation source. The spot size of the laser beam was about 0.4 $cm^2$. The optical signal was collected and dispersed by a HORIBA iHR550 imaging spectrometer connected with a standard lock-in amplifier technique, and detected by an electric-cooled InGaAs photodetector. The excitation power of the laser was fixed at 85 mW during the temperature-dependent PL measurement. For power-dependent PL measurements, the temperature of the sample was fixed at 60 K. A Janis CCS-150 closed-cycle cryogenic refrigeration system equipped with a LakeShore 325 temperature controller was employed to control the temperature of the samples. All PL spectra were measured with a temperature stability of 0.5 K or better.

## 3 Results and discussion

Figure 1 shows the temperature-dependent PL spectra of $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs under an excitation power of 85 mW. For the PL spectrum at 40 K, it is found that the shape of the peak is asymmetry and a long tail located at the low-energy edge can be observed. The tail and main peaks are located at 1.471 eV (843 nm) and 1.501 eV (826 nm), which are labeled as A and B, respectively. Therefore, there must be more than one type of emission mechanism. The peak A exists at temperatures from 40 K to 90 K, while disappearing when the temperature is above 100 K. It is noted from Fig. 1 that the intensity of peak A decreases significantly with temperature. In contrast, peak B exists for the whole temperature range and dominants the emission. At higher temperatures than 100 K, the emission of peak B changes to a symmetric one. With the increase of temperature, the localized carriers gain enough thermal energy and transform to become free ones. The evolvement characteristic of peak A is consistent with localized states emission (LE). The full width at half-maximum (FWHM) of peak B increases monotonically with the increase of temperature, which is attributed to the influence of intrinsic acoustic phonon and optical phonon scattering. Considering the above analyses, it can be concluded that peak B originates from free-carrier emission (FE).

In order to analyze the evolvement of the peak positions, the peak emission energies of the MQWs as a function of temperature was plotted. The temperature dependence of semiconductor bandgap shrinkage can be well described by the following model, shown as Eq. (1), which was derived by O'Donnell and Chen [22]:

$$E_g(T) = E_g(0) - S\langle\hbar\omega\rangle[\coth(\langle\hbar\omega\rangle/2kT) - 1], \qquad (1)$$

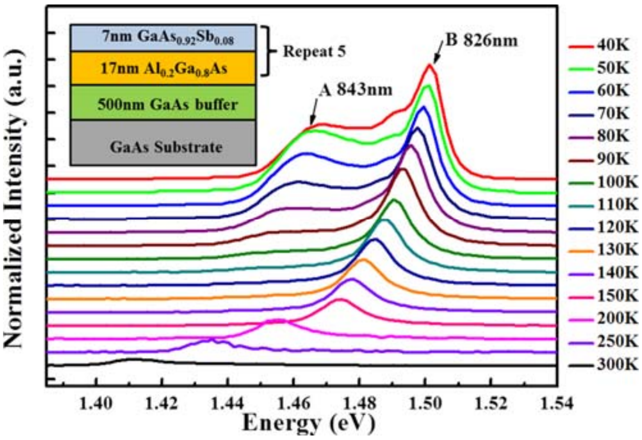

**Figure 1** Temperature-dependent PL spectra of the $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs.

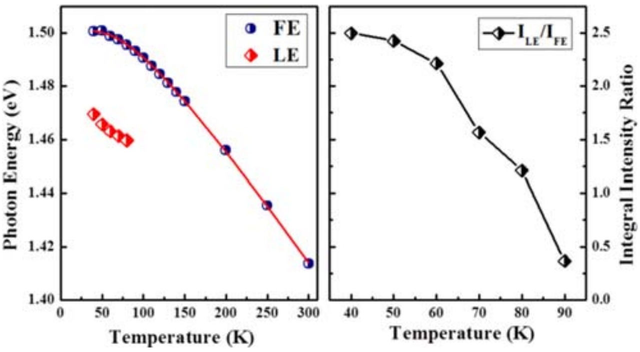

**Figure 2** (a) Temperature-dependent emission peak position of the $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs, the red solid line is fitting curve. (b) Temperature dependent $I_{LE}/I_{FE}$ of the $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs.

where $E_g(0)$ is the bandgap of $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ at $T = 0$ K; $S$ is a dimensionless coupling constant, and $\langle \hbar\omega \rangle$ is an average phonon energy. We calculated the values of $E_g(0)$, $S$, and $\langle \hbar\omega \rangle$ as equal to 1.501 eV, 2.59, and 21 meV, respectively [23]. The theoretical fitting is consistent with experimental data in the full temperature range (40–300 K). Hence, we conclude that the evolvement of peak B conforms to the emitting characteristics of free-carrier emission.

Figure 2b shows the temperature-dependent integrated intensity ratio of LE and FE. It can be observed that the $I_{LE}/I_{FE}$ decreases with temperature from 40 K to 90 K. A competition between FE and LE in a certain temperature range can explain the behavior of the $I_{LE}/I_{FE}$. At low temperatures, the integrated intensity of PL spectra is mainly determined by the broad distribution of the localized states with different energy potentials. With temperature increase, some of the localized carriers with weak localization will be delocalized first. The delocalized carriers will transfer to free carriers or other localized states with stronger localization, which results in the $I_{LE}/I_{FE}$ of PL spectra decreasing. When the temperature further increases up to 100 K, all of the localized carriers will transfer to free carriers. Therefore, the LE emission disappeared. According to Fig. 2a, the depth of localized states can be estimated to be 30 meV at 40 K. Compared with our previous results, the depth of localized states in $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs is higher than $GaAs_{0.92}Sb_{0.08}$ alloy [19]. This phenomenon can be explained by a quantum confinement effect [24].

To further study the characteristics of localized states, excitation power-dependent PL is applied. The PL spectra of $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs under different excitation powers (1–120 mW) at 60 K are shown in Fig. 3. The LE and FE peaks can be clearly observed in all PL curves. At low excitation power, the intensities of LE and FE are comparable. With the increase of excitation power, the PL spectra are dominated by free-carrier recombination. Furthermore, the LE peak of GaAsSb/AlGaAs MQWs shows a significant blueshift with the increase of excitation power. On the contrary, the FE peak is fixed at 1.501 eV without any change.

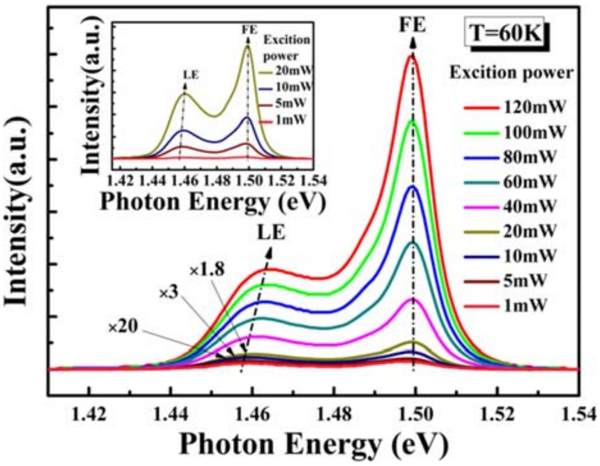

**Figure 3** PL spectra of the $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs under different excitation power at 60 K, the excitation power of the insert is 1–20 mW.

In order to investigate the evolution detail of FE and LE, The peak positions and integrated PL intensity of FE and LE under various excitation powers were analyzed. Figure 4a shows the FE and LE peak positions of $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs under different laser excitation powers. It is observed that the LE peak position exhibits a blueshift when the laser excitation power increased. This blueshift was caused by the state filling of the localized states due to alloy-component fluctuation [19]. It is known that carriers prefer to first fill the localized states at lower energy when the excitation power is low. With the increase of excitation power, localized states will reach saturation and carriers fill in higher-energy levels. Therefore, a clear blueshift of the LE can be observed.

The excitation power-dependent PL intensity is widely used for determining the origin of light emission in semiconductors. It has been established that the PL intensity ($I$)

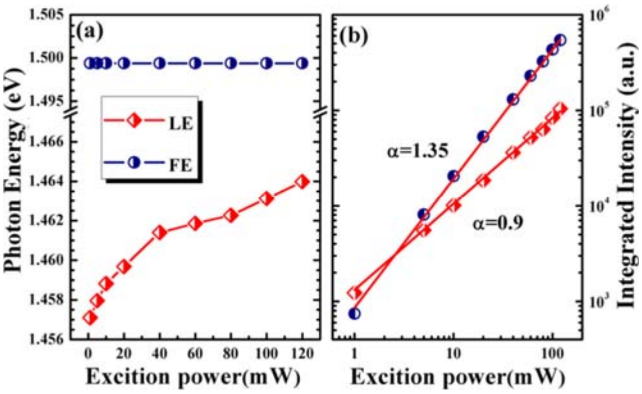

**Figure 4** (a) The FE and LE peak positions of $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs under different laser excitation powers (b) The integrated intensity PL of FE and LE under different laser excitation power, the red solid lines are theoretical fitting curves.

can be expressed as following equation [25, 26]:

$$I = \eta I_0^{\alpha} , \qquad (2)$$

where $I_0$ is the power of the excitation laser radiation, $\eta$ is the emission efficiency, and the exponent $\alpha$ represents the radiative recombination mechanism [26]. For recombination of excitons, the value of $\alpha$ has been reported in the range $1 < \alpha < 2$; For band to band transition, $\alpha \approx 2$; For impurity- or defect-related emission, the value of $\alpha$ is less than 1, such as free-to-bound recombination, donor–acceptor transitions [25, 27, 28].

Figure 4b shows the integrated intensity PL of FE and LE under different laser excitation powers. The symbols display the experimental data of FE and LE and the red solid lines are fitted curves. According to the fitting equation, the parameter $\alpha$ can be obtained to be 1.35 for FE peak and 0.90 for LE peak. This means that the FE peak is confirmed to be free-carrier recombination. The LE peak is different from excitonic recombination, and is attributed to localized state emission.

According to our previous works, the localized states originate from alloy-component fluctuation [19]. In Fig. 4, it is noted that competition exists between LE and FE under different excitation powers. At low excitation power, carriers are confined in localized states. For these reasons, the localized states emission is comparable to free-exciton emission. With excitation increase, localized states reach saturation first and most of carriers exist in the form of free ones. Therefore, the free-carrier emission is dominant subsequently.

**4 Conclusions** In summary, $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs were grown by using MBE and the optical properties of the sample were investigated by temperature-dependent and excitation power-dependent PL measurements. The $GaAs_{0.92}Sb_{0.08}/Al_{0.2}Ga_{0.8}As$ MQWs show a unique emission evolution in the low temperature range. The PL spectra of MQWs present two peaks at temperatures from 40 K to 90 K. The peak on the low-energy side was confirmed as localized states emission by a long tail. The high-energy side peak was confirmed to be free-carrier emission by the temperature-dependent emission peak position. The LE peak exhibited a blueshift with excitation power increasing, which was attributed to the localized states filling effect. Our results provide valuable information with respect to exploring the carrier localization in the GaAsSb/AlGaAs MQWs system. It will be helpful for their practical application for GaAsSb-based MQWs devices.

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