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Photoluminescence from single isoelectronic traps in nitrogen delta-doped GaAs grown on GaAs(1 1 1)A

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ABSTRACT

We have studied photoluminescence (PL) observed from single isoelectronic traps formed by nitrogen pairs in nitrogen δ-doped GaAs layers grown on GaAs(1 1 1)A substrates. The PL was composed of a single peak with a narrow linewidth of ~80 μeV. Polarized PL measurements confirmed that the emission from single isoelectronic traps in nitrogen δ-doped GaAs(1 1 1) is unpolarized irrespective of nitrogen pair arrangements. These results can be explained by in-plane isotropy of the samples, which is consistent with the symmetrical property of GaAs(1 1 1), and demonstrate that utilizing (1 1 1) substrate is an effective means for obtaining unpolarized single photons, which are desirable for the application to quantum cryptography.

1. Introduction

Single-photon emitters are expected to play a key role in the field of quantum information science and technology, such as quantum cryptography [1,2] and quantum computing [3]. In order to realize the single-photon emitters, several candidates are proposed, for example, single molecules [4], nitrogen-vacancy centers in diamond [5], acceptors in semiconductors [6] and semiconductor quantum dots [7,8]. Single isoelectronic traps in semiconductors [9–11] are also promising candidates for single-photon emitters. Concerning the isoelectronic traps in nitrogen doped GaAs or GaP, the emission energies correspond to the configuration of nitrogen pairs [12,13]. In addition, the linewidth of the emission from the isoelectronic traps formed by nitrogen pairs in GaAs or GaP is considerably narrow. Therefore, when utilizing the isoelectronic traps, sharp emission lines with well-defined wavelengths are readily obtained, which is advantageous to the design of distribution Bragg reflectors or filters for enhancing and selecting single photons with specific energies, unlike using semiconductor quantum dots. Thus, we have studied the luminescence from single isoelectronic traps formed by nitrogen pairs in GaAs to demonstrate the potential for the single-photon emitters. We succeeded in observing exciton emission lines from single isoelectronic traps formed by nitrogen pairs in nitrogen δ-doped GaAs layers grown on GaAs (0 0 1) surface [12], and reported twin emission lines which are linearly polarized in the [1 −1 0] and [1 1 0] directions, respectively [13]. Although similar level splitting and polarization properties were reported for semiconductor quantum dots [14], which is due to anisotropic shape of quantum dots, such polarization properties are not suitable for the application to quantum cryptography using unpolarized single photons, such as BB84 protocol [15].

Thus, we have studied photoluminescence from isoelectronic traps in nitrogen δ-doped GaAs grown on GaAs (1 1 1)A substrates which show isotropic in-plane crystal symmetry in principle to obtain randomly polarized photons.

2. Experimental procedure

The samples used in this study were nitrogen δ-doped GaAs layers grown on a semi-insulating undoped GaAs (1 1 1)A substrates by low-pressure metalorganic vapor phase epitaxy. The sources were trimethylgallium (TMG), tertiarybutylarsine (TBA) and dimethylhydrazine (DMHy). The growth temperatures were 630 and 600 °C. To perform nitrogen δ-doping into GaAs, we supplied DMHy flow during the interruption of TMG flow for a few seconds. The nitrogen δ-doped layer was sandwiched between a 300-nm-thick GaAs buffer layer and a 40-nm-thick GaAs cap layer.

We have measured micro-photoluminescence (PL) spectra at 4 K using a diode-pumped solid-state laser (532 nm) as the

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excitation source. The luminescence was dispersed by a 0.75 m monochromator and detected by a charge-coupled device. The spatial resolution and energy resolution of the micro-PL measurement system were ~1 μm and ~30 μeV, respectively. We have also carried out the polarization measurement of the PL spectrum.

3. Results and discussion

Fig. 1 shows a PL intensity map of nitrogen δ-doped GaAs grown on a (1 1 1)A substrate obtained by scanning the sample in one direction. As can be seen from this map, one PL line with narrow linewidth is observed at a specific position, clearly indicating that the emission from a single isoelectronic trap can be successfully detected. This PL line is located at 1.447 eV, which is in agreement with the energy reported for the emission line due to NN_D[8]. Somewhat large spatial distribution (~3 μm) of the emission in this map is probably attributed to the diffusion of exciton.

Fig. 2 shows a PL spectrum obtained at the position where the intensity of the 1.447 eV PL peak is maximized. As shown in this figure, emission line shows a single-peak character and its linewidth is as narrow as ~80 μeV. In addition to the PL shown in Fig. 2, the PL observed from isoelectronic traps formed by other nitrogen pairs, such as NN_A [12] was always composed of a single peak with a linewidth of ~80 μeV. Therefore, the single-peak character is a common feature for nitrogen δ-doped GaAs grown on (1 1 1) substrate, which is completely different from the case of using (0 0 1) substrate, where twin PL peaks were always observed from single isoelectronic traps without relation to the atomic arrangements of nitrogen pairs [10]. The linewidth of the emission from single isoelectronic traps for nitrogen δ-doped GaAs on (1 1 1) substrate is approximately 80 μeV and is larger than that for the case of (0 0 1) substrate, which was in the range 20–50 μeV [10]. The larger linewidth for (1 1 1) may be due to the piezoelectric effect along the [1 1 1] direction, but further experiments will be necessary for clarifying the origin of the linewidth.

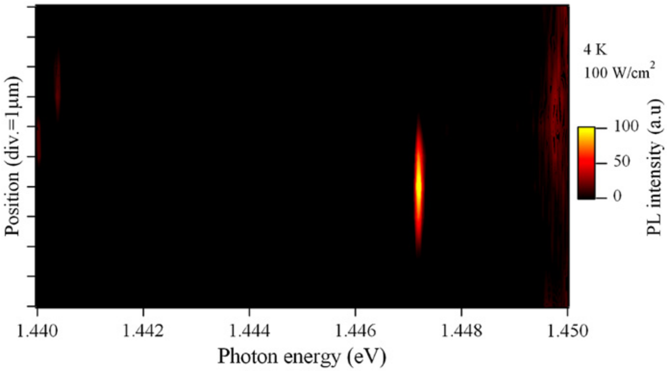

Fig. 1. PL intensity map of nitrogen δ-doped GaAs (1 1 1)A.

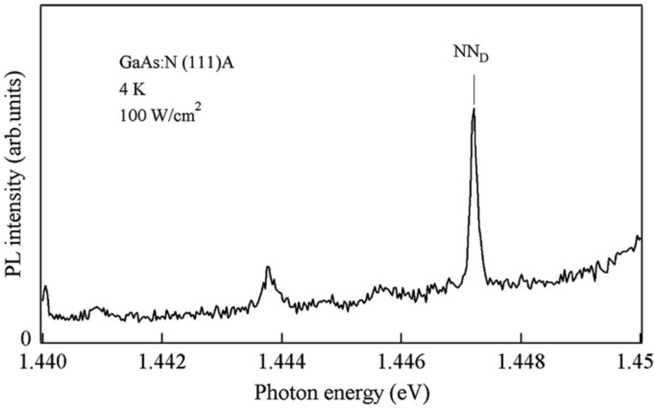

Fig. 2. PL spectrum obtained at the position where the intensity of the 1.447 eV (NN_D) is maximized.

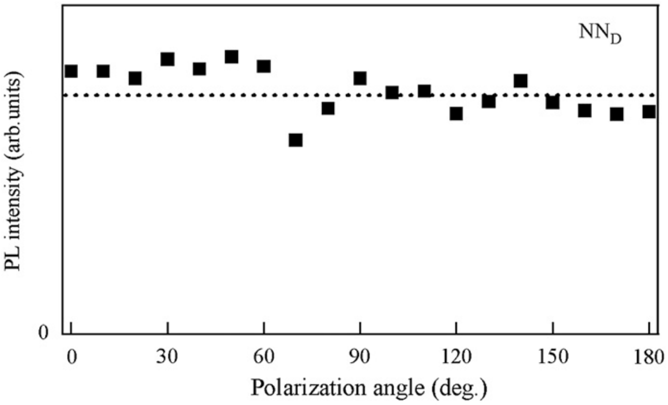

Fig. 3. Polarized PL peak intensity as a function of polarization angle.

Fig. 3 shows the polarized PL intensity of a single isoelectronic trap in nitrogen δ-doped GaAs on (1 1 1) substrate as a function of polarization angle. It is found from this figure that the polarized PL intensity is almost constant at any polarization angle. To make sure that the constant PL intensity is not due to circularly-polarized light but due to unpolarized light, we also measured the polarized PL intensity through a quarter-wave plate and a polarization analyzer, and confirmed that the PL from the single isoelectronic trap in nitrogen δ-doped GaAs(1 1 1) is unpolarized. The unpolarized character was observed for any other single isoeletronic trap in δ-doped GaAs(1 1 1). This polarization property is different from that observed for isoelectronic traps in nitrogen δ-doped GaAs(0 0 1). For nitrogen δ-doped GaAs(0 0 1), the higher and lower energy PL transitions were linearly polarized in the [1 −1 0] and [1 1 0] directions, respectively, and all the twin PL peaks due to single isoelectronic traps show the same polarization properties irrespective of nitrogen pair arrangements [10]. This suggests that the polarization is not due to the atomic configuration of NN pairs [16] but due to the in-plane anisotropy between the [1 −1 0] and [1 1 0] directions in the host crystal, which is possibly caused by strain anisotropy in the sample. In other words, the anisotropy of host-crystal field affects more strongly the polarization properties than local fields due to the configuration of NN pairs, which is predominant for GaP [16]. This is possibly explained by larger exciton Bohr radius in nitrogen δ-doped GaAs, but theoretical examination is required for further discussion. For nitrogen δ-doped GaAs(1 1 1), any emission from single isoelectronic traps shows single-peak and unpolarized character. This indicates that in-plane strain is isoctropic in nitrogen δ-doped GaAs(1 1 1), which is consistent with the symmetry of the host crystal. Therefore, utilizing (1 1 1) substrate is effective means for obtaining unpolarized single photons, which are desirable for the application to quantum cryptography.

4. Conclusions

We have observed exciton emission from single isoelectronic traps in nitrogen δ-doped GaAs grown on GaAs (1 1 1)A surface by high energy resolution micro-PL spectroscopy. The emission from single isoelectronic traps formed by any nitrogen pair exhibited single-peak and unpolarized character. This result shows that the in-plane strain is isoctropic in nitrogen δ-doped GaAs(1 1 1), which is consistent with the crystal symmetry, and demonstrates that the growth on (1 1 1) surface is effective means for obtaining unpolarized single photons.

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