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Photoluminescence Study of Electron Beam-Induced Damage in GaAs/AlGaAs Quantum Well Structures

N. Tanaka, H. Kawanishi, and T. Ishikawa

Optoelectronics Technology Research Laboratory (OTL)

5-5 Tohkodai, Tsukuba Ibaraki, 300-26, Japan

We examined electron beam (EB) induced damage in GaAs/AlGaAs quantum well structures as a function of EB energy and dose by photoluminescence measurement. By using the 5~25 keV EB irradiation with doses less than 1×10^{18} cm^{-2}, we could not find any effect on the photoluminescence properties. Even for a high electron dose of 1×10^{19} cm^{-2}, only a slight reduction of PL intensity was observed. The most remarkable damage was induced by 10 keV EB irradiation with a high dose, rather than 25 keV EB according to the maximum energy loss rate in the QW region.

Introduction

Electron Beam (EB) lithography has been extensively applied to the fabrication of fine structures in semiconducting materials. Recently, novel techniques such as "*in situ* EB lithography"[1)] have been developed with the aim of fabricating ultra fine structures such as quantum wires and/or dots. These processes have an advantage that fine patterns can be easily formed by a direct delineation of a highly focused EB onto the substrate without having to use any thick organic resist. EB is expected to induce less damage than focused-ion-beams[2)] or reactive-ions[3)] because of the small electron mass. However, the damage must be strictly assessed, since in these novel techniques EB is directly irradiated onto the GaAs surface. To our knowledge, there is no report on EB-induced damage by EB irradiation with keV-order energy, except for that regarding the degradation of the two-dimensional electron gas mobility in high-electron-mobility-transistor (HEMT) structures.[4)]

In this work, we investigated for the first time the effect of EB irradiation on the optical properties of GaAs/AlGaAs multiple quantum well (MQW) structures. The EB-induced damage was characterized by the photoluminescence (PL) method for various incident EB energies and doses.

Experiment

MBE-grown MQW structures were used as depth-sensitive probes to assess EB-induced damage. They comprised GaAs quantum wells with various widths of 2, 3, 5, 8, and 15 nm, located at different positions beneath the surface as shown in figure 1. They were embedded in 40 nm AlGaAs barriers. The depth profile of the damage can be determined by the PL intensities from each well of these structures. In our experiment, the depth from the surface of top 2 nm-QW was changed from 40 to 1000 nm by varying the thickness of the cap layers. The irradiated EB was in the energy range of 5~25 keV and in the electron doses of 1×10^{17}~4.5×10^{19} cm^{-2}. Photoluminescence measurements were performed at 77 K using an Ar laser with 5145 Å emission.

Results and discussion

The PL spectra of an as-grown sample and a 10

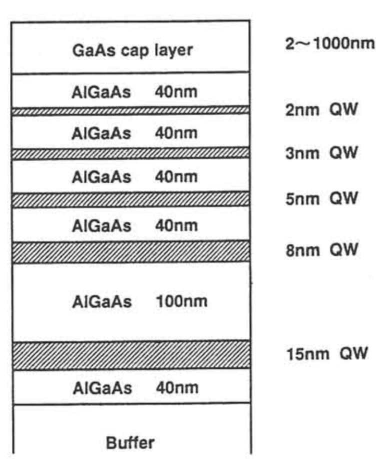

Fig.1. Schematic cross-section of a GaAs/AlGaAs multiquantum well structure grown by MBE

keV EB-irradiated samples are shown in figure 2. The series of light emission corresponds to 5 QWs with well widths of 2, 3, 5, 8, and 15 nm, respectively. These QWs are located at 40, 80, 120, 200, and 260 nm depth from the surface. It was revealed that the PL intensity from the QWs located near the surface decreased by irradiation of more than 1×10^{19} cm^{-2} electron doses. The PL reduction of 2, 3, and 5 nm QWs were a factor of 2 to 3. However, it did not become detectable until

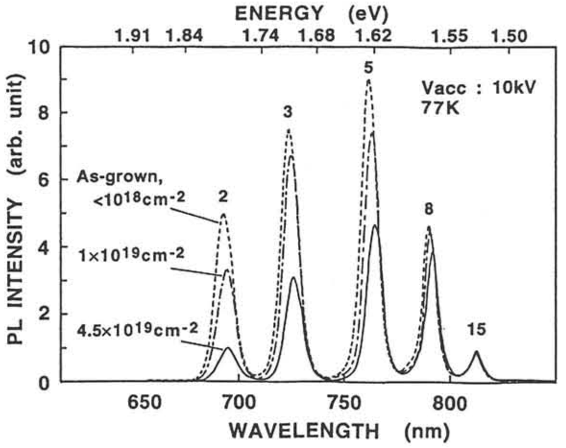

Fig.2. PL spectra of the as-grown and the 10 keV-EB irradiated samples. The thickness of a cap layer is 2 nm.

the electron doses increased up to 1×10^{19} cm^{-2}. The dose dependence of the PL intensity of the topmost 2 nm-QW at a 40 nm depth is shown in figure 3, where the luminescence intensity is normalized by that of the as-grown samples. The intensity did not decrease below an electron dose of 1×10^{18} cm^{-2}, and began to decrease with increased doses over 1×10^{19} cm^{-2}. The deeper QWs, such as 3 nm-QW at an 80 nm-depth and 5 nm-QW at a 120 nm-depth also exhibited a similar dose dependence of PL reduction as the topmost QW. These results are very important from the view point of lithography applications. Since the typical dose levels used for conventional EB lithography and " *in situ* EB lithography " are 1×10^{16} cm^{-2} and 1×10^{17} cm^{-2}, respectively, the effect of EB irradiation on the optical properties of GaAs/AlGaAs systems can be said to be negligible from the present results.

Figure 4 shows the depth dependence of the normalized PL intensities of samples irradiated by various EB energies of 5, 10 and 25 keV. The depths of QWs from the surface were widely changed by increasing the cap layer thickness from 2 to 1000 nm. For 10 keV, the damage extended to 120 nm from the surface. For both 5 and 25 keV, on the other hand, the PL intensity did not decrease in the depth range from 40 to 1000 nm even with doses as high as 4.5×10^{19} cm^{-2}. These EB energy dependence of the damage profile can

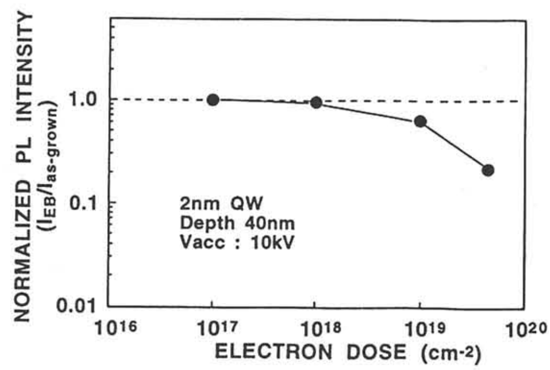

Fig.3. EB dose dependence of PL intensity for 2 nm QW

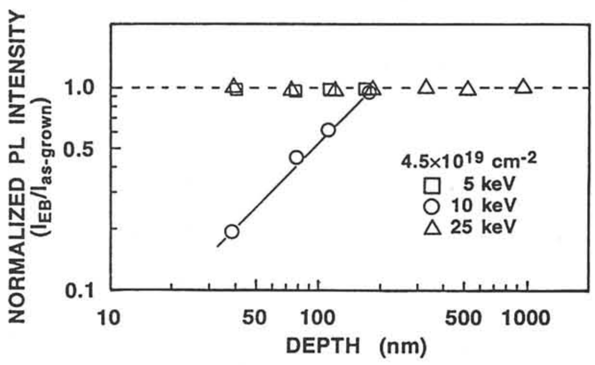

Fig.4. Normalized PL intensity as a function of depth from the surface.

be explained in terms of the electron penetration depth and the energy loss distribution. The electron diffusion model which was proposed by C.A.Klein[5] gives an insight on the distribution of the energy loss. In this model, the incident electrons penetrate into the target to a distance of R_1 without any collision and then diffuse evenly in all directions in the target with range R, which satisfies $R_s=R_1+R$ (R_s is obtained from the theory of Soejima [6] schematically shown in figure 5). The energy loss rate dE/dx in GaAs is given by,

$$dE/dx=(E_0/R_s)\,(\mu R_s/4)\,(1+\mu R_s|x-R_1|)\exp(-\mu R_s|x-R_1|),^{5)}$$

where μ is absorption coefficient of the target, E_0 is incident EB energy, and x is the distance from the surface.

The calculated energy loss rates for 5, 10, and 25 keV are shown in Fig.5. For 5 keV, the energy loss rate has sharp distribution near the surface. With increased EB energies, the energy loss-rate decreases due to the reduced cross section of electron collisions with the target, resulting in a broadening of the depth profile as shown in Fig.5. Thus, on the low-energy side, the highly damaged region is located in a region that is sufficiently shallow so that the QWs are not affected in the present experiment. On the high-energy side, even

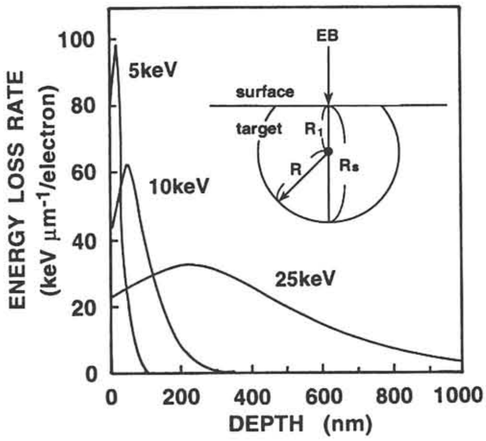

Fig.5. EB energy dependence of depth profile of energy loss rate.

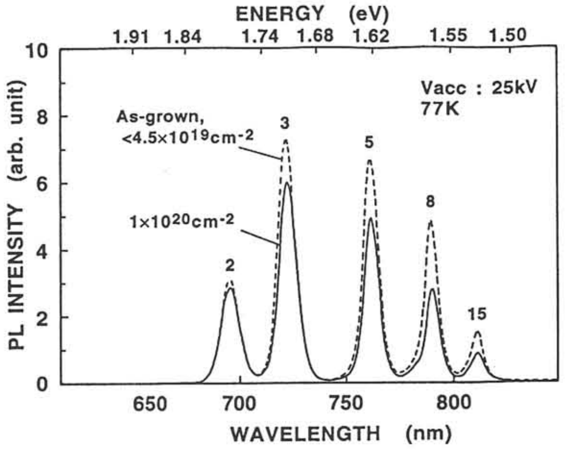

Fig.6. PL spectra of the as-grown and the 25 keV-EB irradiated samples. The thickness of a cap layer is 2 nm.

though an electron penetration depth becomes sufficient, the energy-loss rate is too low to cause any detectable damage to the QWs. In order to make sure of this interpretation, we tried to detect the 25 keV-EB irradiated damage by using samples with a very high electron dose. The PL spectrum of a sample with a 2 nm-cap layer irradiated by 25 keV-EB with electron doses as great as 1×10^{20} cm^{-2} is shown in figure 6. In contrast to the results of the 10 keV-EB (Fig.2), these QWs located deeper than 120 nm-depth exhibited a greater reduction of PL intensities than did the QWs located near the surface. Thus, the high-energy EB-induced damage is believed to be deeply and broadly distributed.

From the above-mentioned results, the EB-induced defects which affect the optical properties of GaAs/AlGaAs systems seem to be correlated with the energy-loss distribution of incident electrons. Similarly, the EB energy dependence of the damage profile was reported for the mobility degradation of a two-dimensional electron gas in HEMT structures.[4] However, it should be noted that the dose level that induces the mobility degradation is 1×10^{16} cm^{-2}, two orders of magnitude lower than that of the present work inducing PL degradation. This means that the charged defects which affect the electrical transport properties are not the cause of optical degradation.

Finally, we compare the defect characteristics of the present work with those of MeV-EB introduced defects. It was reported that EB with a few MeV energy generates Frenkel-type defects acting as deep levels.[7] They exhibited the characteristic annealing behaviors. That is, they were annealed out at 200 °C for a few minutes. The annealing properties of the damage introduced by EB irradiation of 5~25 keV was examined, being different from that of MeV-EB induced defects. Namely, the PL intensity did not exhibit any recovery even after annealing at 400 °C for 1 hour. Therefore, the keV-EB introduced damage may be generated by a different mechanism from that caused by the elastic scattering typical to the case of MeV-EB irradiation. More studies are needed to clarify the origin and the generation mechanism of the keV-EB induced defects.

Summary

The 5~25 keV EB was found to introduce degradation of the optical properties of GaAs/AlGaAs. The effect, however, was not remarkable up to the electron dose of 1×10^{19} cm^{-2}. Moreover, it was almost negligible for 25 keV-EB even with doses as high as 4.5×10^{19} cm^{-2}. These EB energy and dose dependences of the induced damage were interpreted by the electron penetration depth and the energy loss distribution. Since the dose level used for the EB lithography and related processes is below 1×10^{18} cm^{-2}, these processes are proved to be damageless and thus promising for fine structure fabrications.

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