Optical detection of electron-depletion region surrounding metal electrode on a dilute two-dimensional electron gas

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Microscopic photoluminescence images were measured on a dilute two-dimensional electron gas (2DEG) in an n-type modulation doped quantum well at 5 K. We observed electron-depletion regions surrounding metal electrodes formed by annealing of soldered indium or evaporated AuGeNi. The difficulty of forming an ohmic contact to a dilute 2DEG was probably due to the depletion region separating the 2DEG from the metal electrode.

KEYWORDS: micro-PL imaging, quantum well, modulation doping, two-dimensional electron gas, depletion region, ohmic contact

The formation of an ohmic contact to a two-dimensional electron gas (2DEG) is absolutely necessary in transport experiments on the fundamental and applied physics of two-dimensional systems.¹⁻⁴ For n-type GaAs-AlGaAs structures, the annealing of soldered indium or evaporated AuGeNi is conventionally used to form an ohmic contact to a high-density 2DEG. For a dilute 2DEG, however, this method does not always work, and the current-voltage characteristics often exhibit insulating or non-ohmic properties. Since the origin of this problem is not clear and no solution has been found, the trial-and-error approach has been the only way to search for conditions for forming good ohmic contacts.

Compared with transport experiments, optical experiments have advantages for studying energetically and spatially resolved spectra of 2DEGs. Recent experimental works have demonstrated a technique for imaging the distribution of electrons by scanning optical microscopy.⁵⁻⁷ The point of these experiments is that the photoluminescence (PL) spectra show distinct peak structures depending on the background 2DEG density. Negatively charged excitons and/or 2DEG recombination emission dominate the PL in the presence of a 2DEG, whereas neutral excitons appear as the 2DEG density approaches zero. Although near-field microscopy is necessary to study strongly localized or confined electrons,⁵⁻⁷ far-field micro-PL is also available to image the distribution of electrons with spatial resolution of the order of 1 μm.

In this work, we study the problem of forming an ohmic contact to a dilute 2DEG by measuring 2D micro-PL images of an n-type modulation doped quantum well at 5 K around a metal electrode. We found that the annealing of conventional metals, such as indium and AuGeNi, results in the formation of a depletion region in the dilute 2DEG surrounding the metal electrode. In the case of a soldered indium electrode, we observed a depletion region with a width of 20 μm, which completely separated the 2DEG from the indium electrode. In the case of an evaporated AuGeNi electrode, the width of the depletion region was smaller (< 10 μm).

The structure of the sample grown by molecular-beam epitaxy is shown in Fig. 1(a). It consisted of the following layers on a non-doped (001) GaAs substrate: 1-μm (GaAs)9 (Al0.36Ga0.64As)7 superlattice, 6.3-nm GaAs quantum well, 20-nm Al0.36Ga0.64As spacer, 1x10¹¹-cm⁻² Si delta-doping, 450-nm (GaAs)9 (Al0.36Ga0.64As)7 superlattice, and 30-nm GaAs cap layer. On the top surface of different pieces of the sample, we fabricated two kinds of metal electrode, soldered indium and evaporated AuGeNi (5-nm Ni / 300-nm Au0.75Ge0.27 / 20-nm Ni / 50-nm Au), and annealed them at 450 °C for 30 minutes. This recipe is known to work for forming ohmic contact to a high-density 2DEG.

Figure 1(b) shows current-voltage curves obtained by two-terminal measurement. In the case of indium, all of the contacts exhibited an insulating curve. In the case of AuGeNi, almost half of the contacts exhibited ohmic curves, while others exhibited insulating or nonlinear (non-ohmic) curves as indicated in Fig. 1(b). From Hall measurements with good ohmic contacts at 5 K, we estimated the 2DEG density to be 6x10¹⁰ cm⁻².

In our PL measurements, the sample was excited at 1.612 eV by a cw titanium-sapphire laser in the back-scattering geometry shown in Fig. 1(a). The point excitation with intensity of 40 μW was focused to 0.8 μm. The sample was cooled to liquid helium temperature in a cryostat. The collected PL was dispersed in a 0.75-m spectrometer and the system spectral resolution was 0.05 nm. The position of the sample was controlled by an au-

Fig. 1. (a) Sample structure and the geometry of micro-PL measurement. (b) Typical current-voltage characteristics at 5 K for indium and AuGeNi electrodes.

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tomatic stage. This enabled us to measure energetically and spatially resolved spectra of the 2DEG for the 2D micro-PL images.

Figure 2 (a) shows scanning micro-PL spectra measured in 2-µm steps for 100 µm in the direction perpendicular to the indium electrode boundary at 0 µm. At positions of 80, 60, 48, and 20 µm, we observed a single peak denoted by Y at 1.589 eV. Since a dilute 2DEG with a density of $6 \times 10^{10}$ cm$^{-2}$ was formed in the quantum well, we assigned peak Y to the emission of negatively charged excitons or that of 2DEG recombination.8,9) As long as the position was far from the indium electrode, single Y peak dominated the PL spectra. Below 60 µm, another peak denoted by X appeared at 1.591 eV. The energy gap between Y and X peak is 2 meV. We assigned peak X to neutral excitons, which usually appear in non-doped quantum wells.

To confirm these assignments, we measured PL and corresponding photoluminescence-excitation (PLE) spectra, as shown in Fig. 2(b). The solid (dotted) lines are PL (PLE) spectra at the positions of 80, 60, 48, and 20 µm. At 80 µm, the PLE spectrum has a typical double peak structure at $\omega_1$ and $\omega_2$. The $\omega_1$ peak corresponds to peak Y in the PL. At 60 µm, the $\omega_2$ peak shows a red shift, while the $\omega_2$ peak stays at the same energy. At 48 µm, the $\omega_1$ peak loses its intensity and the $\omega_2$ peak exhibits an asymmetrical lineshape. At 20 µm, the $\omega_1$ peak disappears and the $\omega_2$ peak becomes symmetrical. This symmetrical $\omega_2$ peak appears at the same energy as that of peak X in the PL. These spectral evolutions are analogous to the results for a variable-density 2DEG in n-type doped quantum wells reported by other groups.10–13) According to their work, the $\omega_2$ peak corresponds to neutral excitons in the limit of low electron density. This supports our interpretation of peak X being due to neutral excitons.

The PL spectra between 40 µm and 0 µm are dominated by neutral excitons. Below 0 µm, we observed no PL signal because the indium electrode is there. These results indicate that an electron-depletion region is formed near the indium electrode.

The spatial distribution of this depletion region can be imaged by the intensities of peak X or Y. 2D micro-PL images near the indium electrode are shown in Fig.3. They were probed by the intensity of peak X (a) and that of peak Y (b). The scanning step size was 2 µm and the image size was 100 x 100 µm$^2$. Three clear regions denoted by A, D, and M were observed. At the position in region A, we observed weak X emission and strong Y emission, which represents the formation of a 2DEG. In region M, no PL signal appeared because of the indium electrode. In region D, we observed strong X emission and weak Y emission, which indicates electron depletion. This depletion region surrounds the electrode and separates the 2DEG in region A from the electrode. The width of region D was about 20 µm and was almost constant.

Note that this depletion region was observed only after the annealing of indium and not before. The annealing of indium soldered GaAs samples often results in the diffusion of indium metal on the surface along crystallographic directions, which can be seen with a reflection optical microscope. However, the depletion region that we found in this experiment was different from such surface diffusion of metal. Indeed, we observed this depletion region around both the original soldered indium and surface diffused indium. Boundaries between regions A and D were not visible using a reflection optical microscope.

The formation of the depletion region surrounding the metal electrode is consistent with the results of current-voltage characterizations showing no ohmic curve because the depletion region works as a potential barrier and increases the resistivity.8) Thus, we interpreted the difficulty of making ohmic contact to the dilute 2DEG as being due to the formation of a depletion region separating the metal electrode from the 2DEG.

We also measured PL-images of the 2DEG near the AuGeNi electrode. PL-images probed by the intensity of peaks X and Y near the AuGeNi electrode are shown in Fig. 4(a) and 4(b), respectively. The spatial resolution is 2 µm and the image size is 100 x 100 µm$^2$. Four regions, denoted A, B, D, and M, were observed. Region A with weak X emission and strong Y emission corresponds to a 2DEG formed by Si modulation doping. Region M with no PL signal corresponds to the AuGeNi electrode. In region B, we observed weak X emission and strong...
Y emission, which indicates the formation of a 2DEG there. The depletion region D surrounded the electrode and separated the 2DEGs in regions A and B. The width of the depletion region was less than 10 µm.

The depletion region D, or the boundary between D and A, was located about 20-µm away from the AuGeNi metal region M. This depletion region was not observed before the annealing of AuGeNi. These features are common with the case of the indium electrode. However, the 2DEG was observed in region B near the AuGeNi electrode, which was not found for the indium electrode. We conjecture that this 2DEG results from the Ge working as a donor.

The width of the depletion region was rather small (<10 µm) for AuGeNi, compared with that for indium (20 µm). As shown in Fig. 1(b), the current-voltage curve for AuGeNi exhibits a small current while that for indium exhibits an insulating character. These results indicate that the width of the depletion region is related to the current-voltage characteristics. As the width of the depletion region decreases, the contact approaches being an ohmic contact. The width of the depletion region surrounding a metal electrode can be used as an indicator to characterize its poor contact to the 2DEG when the system exhibits an insulating or non-ohmic character.

The formation mechanism of the depletion region is currently unknown, and this is an important subject for future work. Determining the formation mechanism will require more systematic study changing metal compositions, annealing conditions, and sample structures such as the 2DEG density, Si doping density, and spacer thickness. In addition, such study may be a steady scientific approach to finding conditions for making reproducible and reliable ohmic contacts to dilute 2DEGs.

In summary, we measured PL-images of a dilute 2DEG at 5 K and found that the annealing of conventional metals resulted in the formation of a depletion region surrounding each metal electrode. In the case of indium, the width of the depletion region was almost 20 µm, which completely separated the 2DEG from the indium electrode. In the case of AuGeNi, the width of the depletion region was rather small (<10 µm) due to the formation of the 2DEG near the electrode. The difficulty of forming an ohmic contact to a dilute 2DEG is probably due to the depletion region separating the 2DEG from the metal electrode.

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