Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 706-708

Transport Properties of Modulation Doped Structures Grown by Molecular Beam Epitaxy after Focused Ion Beam Implantation

*Masayuki ITOH, Tadashi SAKU, Toshimasa FUJISAWA, Yoshiro HIRAYAMA and Seigo TARUCHA

NTT Basic Research Laboratories
3-9-11, Midori-cho, Musashino-shi, Tokyo, 180, Japan
* present address: *NTT Opto-Electronics Laboratories*
3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa, 243-01, Japan

Modulation doped structures are grown by molecular beam epitaxy after focused ion beam writing. The growth and implantation chambers are connected in a high-vacuum condition for minimizing the effect of growth interruption. The electron channel is depleted by Be^+ implantation, while it is hardly depleted by Au^+ or Au^{2+} implantation. This is because the first implantation forms p-type material, while the second implantation leaves just damage in the n-type material. The Be^+ implantation is used to fabricate narrow wires with electron mobility of 2.1×10^5 cm^2/Vs.

1. Introduction

Molecular beam epitaxial (MBE) growth after focused ion beam (FIB) implantation[1] makes it feasible to fabricate new mesoscopic structures, such as burried quantum boxes and quantum wires. MBE growth after Si-FIB implantation was previously employed to fabricate two-dimensional electron gas in a selected area.[2,3] However, the electrical and optical properties are strongly degraded due to contamination on the ion implanted surface, which usually occurs during the MBE growth interuption. So it is very important to keep high-vacuum level of chambers and the sample transfering between the MBE and FIB chambers.[1] This paper presents transport properties of modulation doped structures grown on a Au^+, Au^{2+} or Be^+ -FIB implanted wafer, which is transfered under the high-vacuum condition between the MBE and FIB chambers. We also use the Be^+ implantation to laterally constrict the electron channel. So far, several types of quantum wires using FIB implantation are reported.[4,5,6] Regarding Ga-FIB quantum wires, the implantation of Ga^+ into $Al_xGa_{1-x}As/GaAs$ heterostructures converts n-type material into π-type material,[7,8] so that electrons are laterally constricted in the unimplanted region. However, there are two main problems in conventional implantation techniques : (1) damage caused by implantation from the sample surface to the region beyond a channel and (2) unintentionally implanted ions in the vicinity of a channel.[5] Both of these degrade electron transport properties.[6] These problems seem to be excluded in our fabrication, since Be^+ implanted regions are located just in the GaAs buffer layer.

2. Sample preparation

Samles were prepared as follows. First, a 800 nm-thick undoped GaAs layer was grown by MBE on (100) oriented semi-insulating (S.I.) GaAs substrate. The grown wafer was then immediately transfered to the FIB system through a high-vacuum chamber. After the scanning of the FIB, the wafer was again returned to the MBE chamber for the over growth of a 100 nm-thick undoped GaAs buffer layer, a 20 nm-thick undoped AlGaAs spacer layer, a 80 nm-thick Si-doped AlGaAs layer and a 20 nm-thick Si-doped GaAs cap layer, successively.

Three types of patterns-squares, lines and wires-were drawn by Au^+, Au^{2+} and Be^+-FIB implantation. The implanted patterns are shown in insets of Fig.1 (a), Fig.2 and Fig.3, respectively. Details of the wire fabrication is described elsewhere.[6] The vacuum level of the chambers were 1.0×10^{-10} Torr in the MBE chamber, 2.0×10^{-9} Torr in the transfer chamber and 7.0×10^{-10} Torr in the FIB chamber, respectively. Implanted dose (Q) were from 5×10^{10} to 1.5×10^{15} cm^{-2}

and implanted acceleration voltage was 69 kV, in which the ion projected range are estimated 17.5 nm for Au^+, 35 nm for Au^{2+} and 200 nm for Be^+.[9] The ion beam diameter was 0.08 μm. Growth temperatures in the MBE chamber were 700 °C for the substrate cleaning, 660 °C for the growth on S.I. GaAs substrate and 680 °C for the regrowth on implanted GaAs layer. After the regrowth, all samles were mesa-etched to a Hall-bar shape without additional annealing. The sample made on the non-implanted region exhibits a sheet carrier concentration (N_S), of 3.9 x 10^{11} cm^{-2}, and an electron mobility (μ), of (2.3 - 3.4) x 10^5 cm^2/Vs at 1.5K after illumination.

3. Transport properties

3.1. Square and line-implanted samples

Figure 1 (a) and (b) show the dose dependence of the resistivity and sheet carrier concentration for the square-implanted samples. They were estimated from four-terminal (4TM) and Hall measurements. Figure 2 shows the dose dependence of the two-terminal resistance for the line-implanted samples. The Au^+ and Au^{2+} square-implanted samples exhibit an increase in resistivity when the dose becomes high. The increased resistivity arises mainly from the decrease in electron mobility, although the sheet carrier concentration gradually decreases with increasing ion dose. Consequently the Au^+ line-implanted sample shows only a slight increase of resistance with increasing ion dose. This indicates that a barrier which would lead to the depletion of the electron channel does not form. Implantation-induced damage decreases the mobility and increases the resistivity in the square-implanted sample as well as the resistance in the line-implanted sample when the Au^+ dose is raised above 10^{14} cm^{-2}. On the other hand, a drastic increase in resistivity of the square-implanted samples appears even at a dose around 10^{13} cm^{-2} in case of Be^+, although Be^+ is lighter and assumed to cause less damage than Au^+. This increased resistivity arises mainly from the drastic decrease in sheet carrier concentration rather than the decrease in electron mobility. Consequently, the Be^+ line-implanted sample displays a drastic increase in resistance around the dose of 10^{13} cm^{-2} as shown in Fig.2.

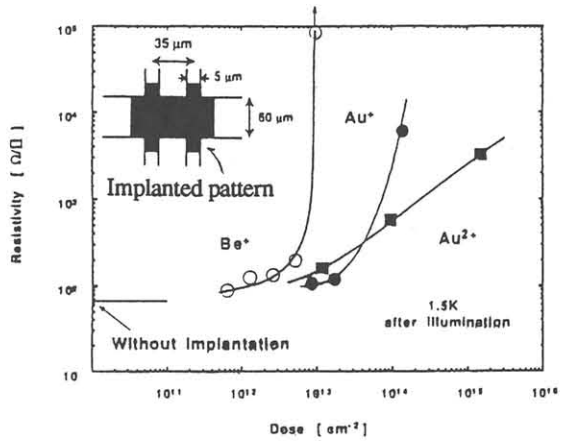

Fig.1 (a) Dose vs. resistivity for Au^+, Au^{2+} and Be^+ square-implanted samples.

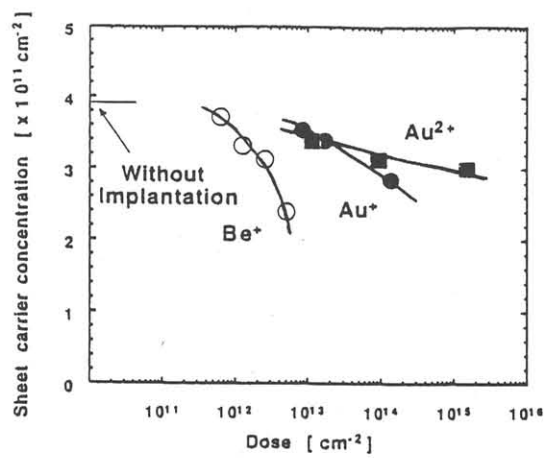

Fig.1 (b) Dose vs. sheet csrrier concentration for Au^+, Au^{2+} and Be^+ square-implanted samples.

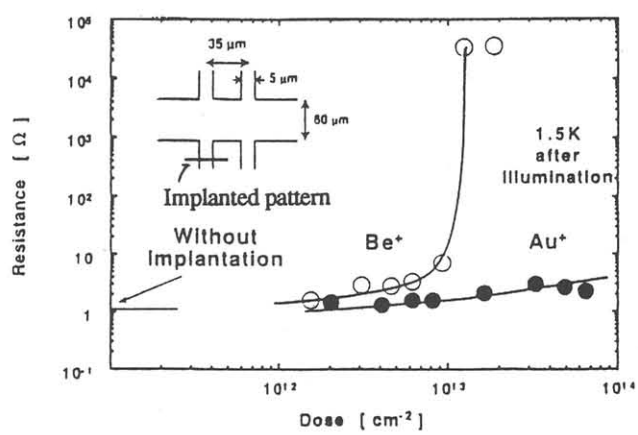

Fig.2 Dose vs. two-terminal resistance for Au^+ and Be^+ line-implanted samples.

These results confirm that the Be^+ implanted regions are converted into p-type material at a dose greater than 10^{13} cm^{-2}.

3.2. Wire structure samples

Figure 3 shows the 4TM conductance as a function of structure width for the wire structures. The conductance was measured using the voltage probe 10 μm spaced for a constant current injection. The Be^+ dose Q was 6.5 x 10^{13} or 1.3 x 10^{14} cm^{-2}, which is higher than the critical dose of 10^{13} cm^{-2} illustrated in Fig.3. Depletion spreading is assumed to be about 0.8 μm for both doses. So the effective wire width is obtained by subtracting the depletion thickness from the structure wire width. The conductance is appreciably low for the structures with a high Q of 1.3 x 10^{14} cm^{-2} probably due to the implantation-induced damage. For Q = 6.5 x 10^{13} cm^{-2}, the conductance becomes high in the whole range of wire width. N_S and μ gradually decrease from 3.8 to 3.4 x 10^{11} cm^{-2} and 2.8 to 2.1 x 10^5 cm^2/Vs, respectively as the effective wire width decreases from 4.2 to 0.1 μm. The decrease of μ is assumed to be due to the remaining damage.[6] These results demonstrate the potential of fabricating these interesting burried narrow wire structures with high quality although the fabrication process is not yet optimized.

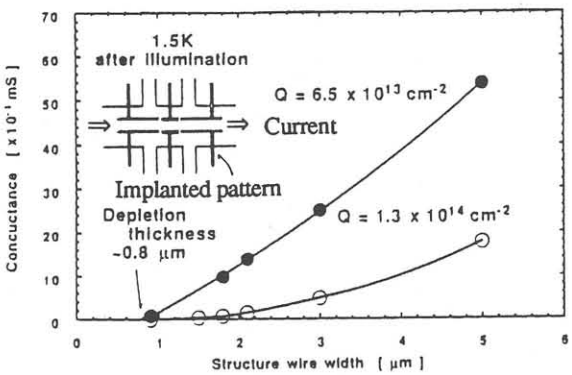

Fig.3 Conductance as a function of structure wire width for Be^+ implanted wires.

4. Summary

The modulation doped structures grown by MBE after FIB implantation are fabricated which are transfered under a high-vacuum condition. Three types of patterns-squares, lines and wires-are drawn by Au^+, Au^{2+} and Be^+-FIB implantation. The mobility of the electron channel above the burried Au^+ or Au^{2+} is decreased by the implantation-induced damage for the implantation dose more than 10^{14} cm^{-2}. The electron channel is hardly depleted by the damage. On the other hand, the electron channel is depleted by the burried Be^+ for a dose more than 10^{13} cm^{-2}. This drastic increase of resistivity arises from a decrease in sheet carrier concentration because the Be^+ implanted region is converted into p-type material. Wire type structures are fabricated using the Be^+-induced depletion regions. Avoiding one of main problems for unimplanted ions, the narrow wire with the effective wire width of 0.1 μm exhibits N_S = 3.4 x 10^{11} cm^{-2} and μ = 2.1 x 10^5 cm^2/Vs.

5. References

1) T. Ishibashi, A. Fischer, A. D. Wieck and K. H. Ploog: Jpn. J. Appl. Phys. **32** (1993) L742

2) A. Kawano, H. Arimoto, H. Kitada, A. Endoh and T. Fujii: Jpn. J. Appl. Phys. **30** (1990) L71

3) H. Arimoto, A. Kawano, H. Kitada, A. Endoh and T. Fujii: J. Vac. Sci. & Technol. **B9** (1991) 2675

4) S. Nakata, S. Yamada, Y. Hirayama, T. Saku and Y. Horikoshi: Jpn. J. Appl. Phys. **29** (1990) 48

5) S. Nakata, Y. Hirayama, S. Tarucha and Y. Horikoshi: J. Appl. Phys. **69** (1991) 3633

6) M. Itoh, T. Saku and S. Tarucha: Jpn. J. Appl. Phys. **31** (1992) 4487

7) K. Nakamura, T. Nozaki, T. Shiokawa, K. Toyoda and S. Namba: Jpn. J. Appl. Phys. **24** (1985) L903

8) Y. Hirayama and H. Okamoto: Jpn. J. Appl. Phys. **24** (1985) L965

9) J. F. Giggons, W. S. Johnson and S. W. Mylroie: *Projected Range Statistics* (Dawden, Hutchingson & Ross Inc., Stroudburg, 1975) 2ed.