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Contact metallization and substrate doping and annealing temperature dependences of the contact resistivity

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ABSTRACT

We fabricated reliable contact structures on *n*-type GaAs using contact materials Au, Ge and Pd with layer thicknesses 100 nm, 50 nm and 10 nm, respectively. The contact resistivities for the structures were measured using transmission line model. Contract structures were studied in dependences of the substrate doping density and annealing temperature. The contact resistivity was found to decrease with increasing annealing temperature up to ~180° C. However, a further increase of the annealing temperature, it increased. The contact resistivity was also found to decrease with increasing substrate doping density. The transfer characteristics and morphological study of the contact indicated an ohmic contact with low contact resistivity. The results, however, show that the inter-diffusion between contact materials is an important factor responsible for the low-resistivity transparent contacts and that using the proposed recipe transparent contacts could be achieved for a wide range of *n*-type substrate doping density.

KEYWORDS

Semiconductor;
Contact resistivity;
Composite material;
Annealing;
Lithography.

INTRODUCTION

Transparent or low-resistance ohmic contacts of small size are very required for future reliable applications in low-dimensional devices. For the ohmic contacts to *n*-GaAs, Au-Ge based materials, such as AuGe/Au, AuGe/Ni and AuGe/Ni/Au have widely been used[1-9]. For example, the commonly used spiking ohmic contact AuGe/Ni is achieved by alloying an AuGe/Ni multilayer structure at high temperatures, generally higher than the Au-Ge eutectic temperature (361 ^{0}C), for a short period of time[9]. However, this metallization presents several drawbacks mainly due to the problematic control of the alloying liquid phases because the ohmic behaviour of the Au-Ge based contacts is known to be a result of liquid phase reactions[9, 10]. The AuGe/Ni metallization therefore presents several serious disadvantages, such as poor contact edge definition and large spread of the contact resistivity within a single wafer (i.e. the surface of the electrodes usually separate to about 500 nm size in the Au- or Ge-rich region after alloying), problems in reproducibility and insufficient contact reliability owing to the presence of the β-AuGe phase (liquid-like flow) of low melting point in a contact with GaAs substrate[5]. This edge spreading could limit the use of the AuGe/Ni contact in GaAs-based devices, where the maintenance of the low-dimensionality is essential.

Contact structures studied so far are exclusively on substrates of moderate-to-high *n*-doping density. But, some future applications, in particular spintronic devices, lightly doped semiconductors are desirable. Therefore, the study of making devices on substrates having a wide range of doping density is required. Moreover, the low-temperature process is also important.

In the present work, we fabricated transparent contact structures on *n*-type GaAs using contact materials Au, Ge and Pd with layer thicknesses 100 nm, 50 nm and 10 nm, respectively. Contract structures were studied in dependences of the substrate doping density and annealing temperature. The results were discussed.

EXPERIMENTAL

Substrates were semi-insulating GaAs (100) wafers with Si-doped surface layers (0.2 nm, ~0.1 kΩ/sq) prepared by MCVD. For the substrate doping-density dependence, samples with various carrier densities (known from Hall measurements) were used. Prior to contact deposition, the substrates were cleaned using conventional organic solvents. The native surface oxide was then removed using HCl:H_2O (1:1 vol.) followed by a de-ionized water rinse and blown dry with nitrogen before loading the substrates in the evaporation chamber. Au(100 nm)/Ge(50 nm)/Pd (10 nm) contact samples were then deposited on the substrates, with Pd layers adjacent to the GaAs substrates, using an e-beam evaporator with a base pressure of ~5x 10^{-8} Torr. A scheme of the contact structure showing contact metallization is shown in Figure 1. The contact metallization was annealed in a tube furnace in flowing nitrogen at different temperatures to study the annealing temperature dependence. The specific contact resistivity was measured following the transmission line model[11] and using two- and four-terminal measurements and a HP4145B parameter analyser to extract *I-V* curves and resistances. In the calculation, we assume that the parasitic prove resistance is accurately known and subtracted from the measurement results[12].

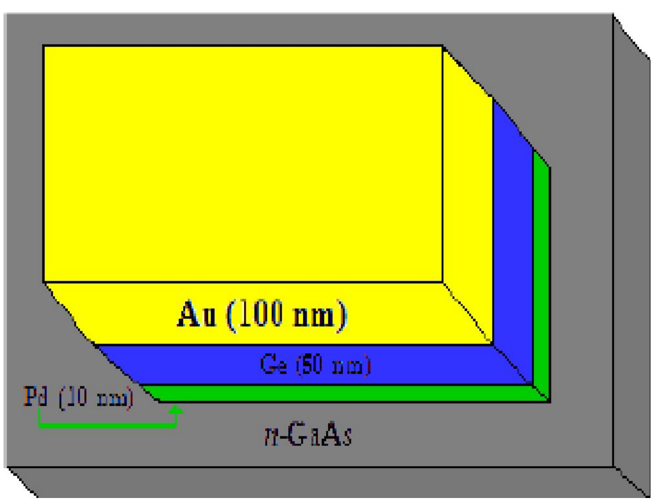

Figure 1 : A scheme of the investigated contact structure showing contact metallization. Only one contact pad is shown on the *n*-GaAs substrate.

RESULTS AND DISCUSSION

Contact structures of the type Au(100 nm)/Ge(50 nm)/Pd (10 nm) were deposited and metallized. In order to find out the better annealing conditions, we study the annealing temperature dependence of the contact structure. Figure 2 shows the contact resistivity as a function of annealing temperature for the fixed annealing time of 1 h. As found, the contact resistivity first decreases with annealing temperature and then increases. The minimum value of ~10^{-6} Ω cm^2 is obtained at 180 ^{0}C. It was also found that the same resistance value for a contact structure annealed at comparatively higher temperature can be achieved by annealing it for

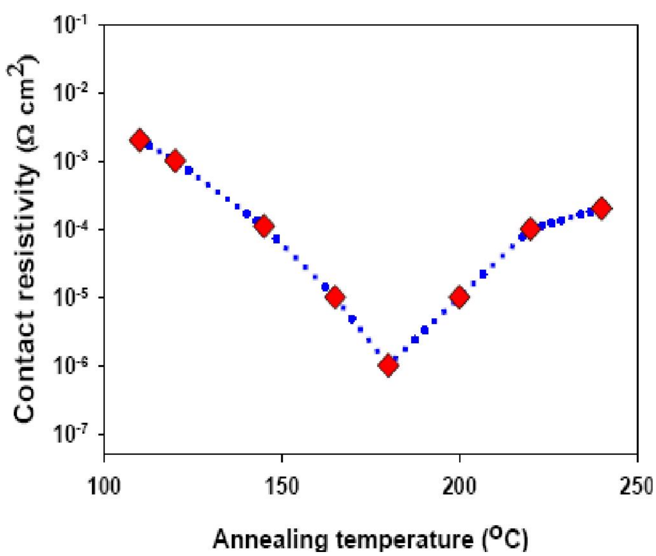

Figure 2 : Dependence of specific contact resistivity on the 1-hour annealing temperature for the contact (n_D = 1x10^{18} cm^{-3}). Points show the averages of the experiment data obtained from several experiments.

a comparatively shorter time.

When the contact structure is annealed at 180 °C for 1 h, the reactions begin at the Pd–GaAs interface to form a metastable Pd_4GaAs phase at lower temperature. However, this ternary phase is decomposed at elevated temperatures, near 180 °C, driven by the excess Ge for the formation of PdGe. This process results in a regrown n^+-GaAs layer doped with Ge, where the excess amorphous Ge remains on top of the PdGe layer because the transport of the excess Ge across the PdGe layer to form an epitaxial Ge layer on the regrown n^+-GaAs layer is not expected at this temperature, and consequently, the conductivity of the excess amorphous Ge is enhanced (as a result of the in-diffusion of Au into the excess Ge). Thus, the factors which are crucially responsible for the observed low contact resistance for the contact annealed at 180 °C for 1 h are the solid phase regrowth, inter-diffusion between Au and Ge and the enhancement of the conductivity of the excess Ge due to the incorporation of Au. It was also found that the as-deposited contact sample structure was not ohmic (even non-ohmic after annealed at 130 °C for 1 h). However, the contact Au(100 nm)/Ge(40 nm)/Pd(10 nm) annealed at 180 °C for 1 h displayed good ohmic behavior with the lowest contact resistivity (~10^{-6} Ω cm^2).

Dependence of contact resistivity on the substrate doping density is shown in Figure 3. As can be seen, the variation is an inverse relationship for the whole rage of doping density. The experiment was repeated several times. In each experiment, samples of different substrate doping densities underwent pattering, deposition, processing and annealing with the same conditions at the same time in order to allow as much control as possible within the experiment. A least-squares log-log fit to the average of the experimental data was made, which gives the relationship $\rho_c \propto n_D^m$ with m=1/2, where ρ_c is the specific contact resistivity and n_D is the substrate doping density. From a theoretic calculation for the AuGe/Ni contacts, Braslau[9] predicted the same type (power) of relationship with m=1. It is worthy to note here that his theories invoked spreading resistance due to laterally inhomogeneous contacts, or a high barrier due to a thick n^+ surface region much greater than the depletion width. In the present case, the resistance of the contacts are most likely not limited by the above reasons because of a naturally low barrier at the Pd/GaAs interface or of an effective lowering of the interfacial barrier due to the creation of a thin n^+ interfacial region, or both. The substrate doping density dependence also agrees with the experimental results for the Pd-In-Ge contacts as well as with the results for the Au-Ge contacts using δ-doped surface layers to n-GaAs[6, 13]. The V-I characteristics of a typical Au(100 nm)/Ge(50 nm)/Pd (10 nm) contact on n-GaAs (annealed at 180 °C for 1 h) is shown in Figure 4. The linear fit to the experimental data indicates a good ohmic contact.

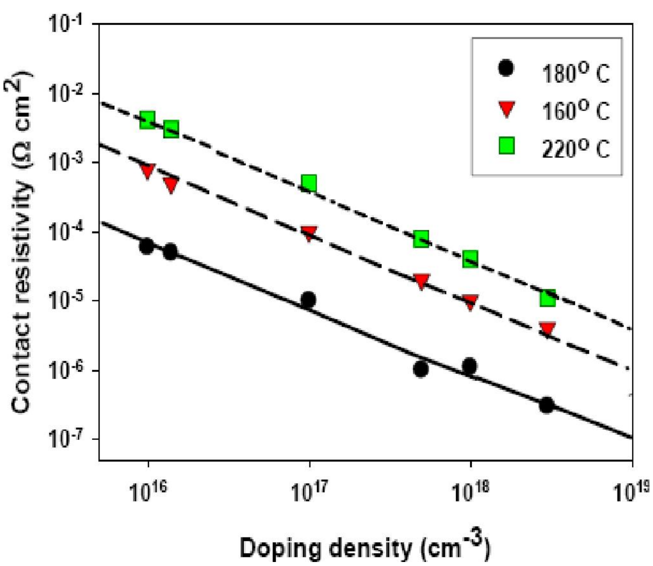

Figure 3 : Specific contact resistivity as a function of the substrate doping density for the contact annealed at different temperatures. Points are the experimental data and the lines are the least-squares log-log fits to the data.

The interfacial morphologies were studied. As observed, the deposited contacts are morphologically good with, e.g. good contact edges and small spread of the contacts, which make them suitable for the contacts of small areas, for example, for large-scale integration circuits. Here, ohmic contacts with low contact resistance are obtained by a process of low-temperature anneal. The low-temperature contacts can be suitable for the fabrication of proton-implanted stripe geometry diode lasers where the higher anneal temperature (~ 450 ^{0}C) of the more commonly used AuGe/Ni contact causes the proton damage to be partially removed, resulting in some current leakage[14, 15]. In addition, these low-temperature annealed contacts result in a better surface for wire bonding and exhibit better stability under high-temperature atmospheric aging than do the conventional AuGe/Ni contacts. Thus, they may find use in a wide variety of devices requiring highly transparent contacts to *n*-type GaAs-based materials. The reproducibility and bondability were also studied and found to be good reproducible and strong wire bondable.

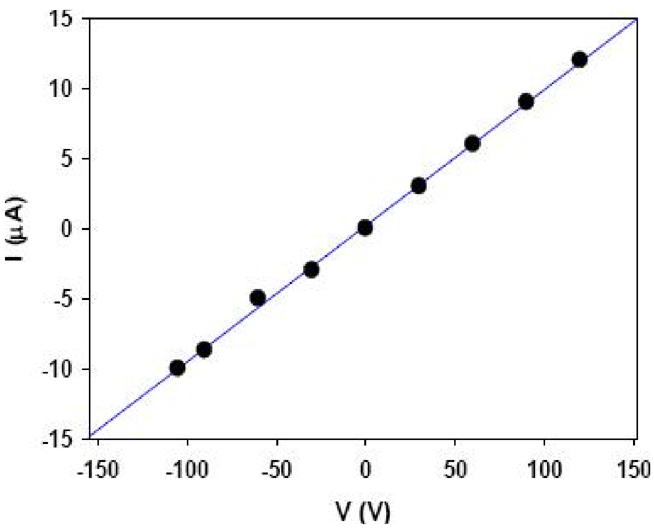

Figure 4 : V-I characteristics of a typical Au(100 nm)/Ge(50 nm)/Pd (10 nm)/*n*-GaAs contact (annealed at 180 °C for 1 h).

CONCLUSIONS

Reliable contact structures on *n*-type GaAs using contact materials Au, Ge and Pd with layer thicknesses 100 nm, 50 nm and 10 nm, respectively, were fabricated. The contact resistivity for the structures was measured using transmission line model and they were studied as a function of the substrate doping density and annealing temperature. The contact resistivity was found to decrease with increasing annealing temperature up to ~180° C, and a further increase of it, the contact resistivity increased. The contact resistivity was also found to decrease with increasing substrate doping density. The V-I characteristics and morphological study of the contact were studied. The obtained results gave the recipe of highly transparent contacts (i.e. ohmic contacts with low contact resistivity). The contact formation mechanisms were also discussed.

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