Novel low-resistance ohmic contact to n-type GaAs using Cu$_3$Ge

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We show that $\epsilon_1$-Cu$_3$Ge forms a low-resistance ohmic contact to n-type GaAs. The $\epsilon_1$-Cu$_3$Ge contact exhibits a planar and abrupt interface and contact resistivity of $6.5 \times 10^{-7} \, \Omega \, \text{cm}^2$ which is considerably lower than that reported for Ge/Pd and AuGeNi contacts on n-type GaAs with similar doping concentrations ($\sim 1 \times 10^{17} \, \text{cm}^{-3}$). The contact is electrically stable during annealing at temperatures up to 450 °C. We also show that in the Ge/Cu/n-type GaAs system, the contact remains ohmic over a wide range of Ge concentration that extends from 15 to 40 at. %.

Alloyed AuGeNi contacts are the most commonly used ohmic contacts to n-type GaAs with a contact resistivity $\rho_c$, in the $10^{-6} \, \Omega \, \text{cm}^2$ range. This metallization, however, often results in a nonplanar interface morphology and the contacts are generally unstable when annealed at high temperatures due to the presence of the low melting point ($T_m \sim 360 \, ^\circ \text{C}$) $\beta$-AuGa phase. To improve the thermal stability of these eutectic-based AuGeNi contacts, low Au content NiGe(Au)W ohmic contacts have recently been developed. However, these contacts exhibit a relatively high contact resistance after annealing at high temperatures (400 °C) as also do the In-based ohmic contacts. To overcome the problems associated with the interface morphology of the alloyed contacts, ohmic contacts of a nonalloyed nature have been proposed based on molecular-beam epitaxy (MBE). However, this technique requires ultrahigh vacuum processing. In recent years, a metallization system that yields nonalloyed and low resistance ohmic contacts to n-type GaAs has been proposed based upon the concept of solid-phase epitaxy. The contact uses a metal layer (palladium) in contact with the GaAs surface onto which a layer of amorphous Ge is then deposited. The thicknesses of the Ge and Pd layers are chosen such that, upon annealing, the entire layer of Pd is consumed in the formation of a PdGe layer through which excess Ge is transported to grow epitaxially on the GaAs substrate. Annealing the Ge/Pd contacts at temperatures higher than 325 °C after contact formation, however, was found to always result in an increase in contact resistance. In this letter, we report on a novel, more thermally stable, low-resistance ohmic contact to n-type GaAs using the $\epsilon_1$-phase of Cu$_3$Ge. We have recently discovered that the $\epsilon_1$ phase of Cu$_3$Ge has a long-range ordered monoclinic crystal structure, exhibits a low metallic resistivity of $\sim 6 \, \mu \Omega \, \text{cm}$ at room temperature. We also show that metal–semiconductor field-effect transistors (MESFETs) with the $\epsilon_1$-Cu$_3$Ge ohmic contacts exhibit a considerably higher transconductance compared to devices that employ Ge/Pd and AuGeNi contacts.

The Cu$_3$Ge contacts were formed by deposition of a Cu layer (122 nm) followed by a Ge layer (78 nm) on 1-μm-thick n-type GaAs epitaxial layers [doped with Si to a concentration of $(1-3) \times 10^{17} \, \text{cm}^{-3}$] at room temperature and subsequent anneal. The epitaxial layers were grown by MBE on semi-insulating GaAs substrates. The thicknesses of the Cu and Ge layers required for Cu$_3$Ge formation were determined assuming bulk density for Cu and Ge. The substrates were chemically cleaned in a solution of HCl:H$_2$O (1:1 by volume) until they were completely hydrophobic. The substrates were inserted into the deposition chamber immediately after chemical cleaning. The Cu and Ge layers were deposited using electron-beam evaporation in a pressure of $\sim 1 \times 10^{-7}$ Torr at a rate of 1 nm/s. This was followed by a 30-min in situ anneal at 400 °C in the deposition chamber in a pressure of $\sim 5 \times 10^{-7}$ Torr. Electron diffraction measurements showed that such an anneal is sufficient to form the ordered monoclinic $\epsilon_1$ phase of Cu$_3$Ge ($a=0.2631$ nm, $b=0.4200$ nm, $c=0.4568$ nm, and $\gamma=89^\circ$ 41 s). For current–voltage ($I–V$) measurements, the deposition was made through a metal mask defining a two-dimensional array of circular contacts with a diameter of 380 μm and a spacing of 1.85 mm. Secondary ion mass spectrometry (SIMS) was used to monitor the formation of Cu$_3$Ge and the reaction with the GaAs substrate.

Standard photolithography was used to pattern the substrates for transmission line measurements (TLM) and for MESFET devices with a n-type channel layer 0.3 μm thick doped to $3 \times 10^{17} \, \text{cm}^{-3}$. After patterning and etching mesa structures, source/drain contact windows were defined and the samples received the HCl:H$_2$O (1:1) treatment immediately before the deposition of the contact layers [Ge/Cu on GaAs (100)]. After lift-off, the samples were annealed at 400 °C for 30 min for the ohmic contact formation. The samples were then further processed for recess gate deposition. A layer of Cu and for comparison, a layer structure of Au/Ti was used as the gate material. The specific contact resistivity and the characteristics of the MESFET devices were then determined.

As can be seen from Fig. 1(a), the $I–V$ characteristics measured between adjacent $\epsilon_1$-Cu$_3$Ge contacts to n-type GaAs ($1 \times 10^{17} \, \text{cm}^{-3}$) at room temperature are linear. The contacts remain ohmic over the temperature range 300–50

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K. Also, for contacts formed with Ge deposited first followed by the Cu layer the $I–V$ characteristics are very similar to those shown in Fig. 1(a). These results are in marked contrast to those reported for the Ge/Pd contacts,10 which show that the contacts do not display ohmic behavior if Ge is deposited first even after a 2-h anneal at 450 °C. In the $\epsilon_1$-Cu$_3$Ge/GaAs system, no epitaxial Ge layer is detected and the $\epsilon_1$-Cu$_3$Ge layer which exhibits a polycrystalline structure, is in contact with the GaAs substrate. The interface between the $\epsilon_1$-Cu$_3$Ge layer and the GaAs is planar and abrupt to within atomic dimensions (~1 nm) as revealed by high resolution cross-sectional transmission electron microscopy.14

Since pure Cu forms Schottky barrier contact on $n$-type GaAs (100) with a barrier height of 0.92 eV,15 it is then interesting to examine the effect of varying the Ge concentration on the ohmic behavior. Contact layers with Ge concentration ranging from 15 to 40 at. % were investigated. Electron diffraction measurements12 showed that at 15 at. % Ge, the contact layer after annealing at 400 °C for 30 min consists entirely of the hexagonal close-packed $\xi$ phase, while at 40 at. % Ge, it consists of the $\epsilon_1$ phase (Cu$_3$Ge) and a small proportion of Ge (here the Ge grains are found to be epitaxial in nature14). As can be seen from Figs. 1(b) and 1(c), both the contacts formed with 15 and 40 at. % Ge layers still exhibit linear characteristics. These results thus show that the Ge/Cu contacts remain ohmic over a wide range of Ge concentration.

It is evident from our results on contacts formed with the $\xi$ and $\epsilon_1$ phases of Cu–Ge alloys which do not produce epitaxial layers of Ge on GaAs, that the primary reason for the observed ohmic behavior is not due to a Ge/GaAs heterojunction. However, for contacts formed with Ge in excess of that required for $\epsilon_1$-Cu$_3$Ge formation which produce epitaxial grains of Ge, the heterojunction may help the current transport across the interface because of a small interfacial energy barrier. Also, the observed ohmic characteristics are not due to the contacting $\xi$ and $\epsilon_1$ phases alone, since these alloy phases are known to form Schottky barrier contacts.16 A likely mechanism for current transport is therefore the tunneling of carriers through a highly doped surface region created by the incorporation of Ge atoms into the GaAs on Ga vacant sites. It can be seen from the SIMS profiles displayed in Fig. 2 for $\epsilon_1$-Cu$_3$Ge/GaAs samples that Ga has diffused into the $\epsilon_1$-Cu$_3$Ge, indicating that the Ga chemical potential in the $\epsilon_1$ phase alloy is lower than that in the GaAs compound. The SIMS profiles obtained for samples with 15 and 40 at. % Ge layers are similar to those shown in Fig. 2. It has been shown15 that pure Cu reacts to form predominantly an arsenide. It would then follow that adding Ge to Cu in the concentration range 15–40 at. % has suppressed the formation of an arsenide and lowered the chemical potential of Ga in the alloy phases, thus causing Ga to outdiffuse from the GaAs which correlates with the observed ohmic behavior. Note also that Cu which is a fast interstitial diffuser, does not, however, penetrate farther into the GaAs than Ge does. Sarma et al.17 found that the diffusion coefficient of Ge in GaAs fit a relation of the form $D(T) = 1.6 \times 10^{-5} \exp(-2.06/kT)$ at temperatures ranging from 650 to 800 °C for Si-doped GaAs. Assuming that the diffusion coefficient of Ge at lower temperatures can be described by this relation, a $D$ of $\sim 7 \times 10^{-21}$ cm$^2$/s is obtained at 400 °C. Our results thus suggest that the diffusion of Ge into GaAs is enhanced at lower temperatures by the formation of Cu germanide. The fact that the $\epsilon_1$-Cu$_3$Ge contacts, as will be shown below, exhibit a remarkably low specific contact resistivity of $6.5 \times 10^{-7}$ Ω cm$^2$ at room temperature suggests that most of the Ga is replaced by Ge,18 since excess Ga outdiffusion is expected to produce a nonstoichiometric condition immediately under the contact thereby creating a region of high resistivity which can result in a high contact resistivity.19 If Cu, on the other hand, occupies Ga vacant sites and becomes a double acceptor,20 it can then compensate the donors producing a high resistivity region under the contact which can dominate the contact resistivity. This is inconsistent with our results. Furthermore, if the creation of an $n^+$ region is responsible for the observed ohmic behavior on $n$-type GaAs, the same mechanism should inhibit the re-

FIG. 1. $I–V$ characteristics at 300 K of contacts with (a) 25 at. % Ge, (b) 15 at. % Ge, and (c) 40 at. % Ge layers on $n$-type GaAs Si doped to $1 \times 10^{17}$ cm$^{-3}$, formed at 400 °C for 30 min. (d) $I–V$ characteristics at 300 K of $\epsilon_1$-Cu$_3$Ge contacts on $p$-type GaAs Zn doped to $\sim 7 \times 10^{16}$ cm$^{-3}$. Scale: 10 mA/div vertical, 50 mV/div horizontal.

FIG. 2. SIMS profiles of an $\epsilon_1$-Cu$_3$Ge/GaAs contact formed at 400 °C for 30 min. Note that only Ga has diffused into the $\epsilon_1$-Cu$_3$Ge. The As signal in the $\epsilon_1$-Cu$_3$Ge is at the background level.
GaAs with similar doping concentrations doped to $m_n \sim 6.5 \times 10^{17} \text{ cm}^{-3}$. Unlike the Ge/Pd system, the placement of Cu initially in contact with the GaAs is not required to result in a low contact resistivity. Also, the contact resistivity remains essentially unchanged after annealing at 450 °C for 2 h. The $\epsilon_1$-Cu$_3$Ge contacts exhibit planar and abrupt interfaces and do not suffer from lateral spreading during high-temperature annealing (450 °C). In addition, their uniformity and reproducibility should allow reliable fabrication of high-density submicron devices.

The average contact resistance $R_c$ of the $\epsilon_1$-Cu$_3$Ge contact and the sheet resistance $R_{sh}$ of the epitaxial layer (0.3 $\mu$m, $n = 3 \times 10^{17} \text{ cm}^{-3}$) determined from TLM measurements at room temperature are 0.125 $\Omega$ mm and 237.5 $\Omega$/$\sqrt{\text{cm}}$, respectively. This value of $R_{sh}$ is in good agreement with that derived from Hall effect measurements. The average specific contact resistivity $\rho_c$ calculated from these data are $6.5 \times 10^{-7} \Omega$ cm$^2$, considerably lower than that reported for Ge/Pd contacts.

Figure 3 shows the $I$–$V$ characteristics and transconductance versus gate voltage characteristics at room temperature for $n$-channel MESFET devices with the $\epsilon_1$-Cu$_3$Ge contacts and a gate length and width of 1 and 25 $\mu$m, respectively. Regardless of whether Cu or Au/Ti was used as gate material, identical device characteristics were obtained. We note that the maximum transconductance is 145 ms/mm at $V_{gs} = 0.35$ V, which is a factor of about 2 higher than found in the same devices with Ge/Pd and AuGeNi contacts. These superior electrical characteristics thus demonstrate that application of the $\epsilon_1$-Cu$_3$Ge ohmic contacts to MESFET devices leads to a significant improvement in device performance.

In summary, we have shown that $\epsilon_1$-Cu$_3$Ge forms a low-resistance ohmic contact ($\rho_c = 6.5 \times 10^{-7} \Omega$ cm$^2$) to $n$-type GaAs with doping concentrations of $\sim 1 \times 10^{17} \text{ cm}^{-3}$. Unlike the Ge/Pd system, the placement of Cu initially in contact with the GaAs is not required to result in a low contact resistivity. Also, the contact resistivity remains essentially unchanged after annealing at 450 °C for 2 h. The $\epsilon_1$-Cu$_3$Ge contacts exhibit planar and abrupt interfaces and do not suffer from lateral spreading during high-temperature annealing (450 °C). In addition, their uniformity and reproducibility should allow reliable fabrication of high-density submicron devices. We have also shown that the contacts remain ohmic over a wide range of Ge concentration extending from 15 to 40 at. %. $n$-channel MESFETs with a gate length and a gate width of 1 and 25 $\mu$m, respectively, using the $\epsilon_1$-Cu$_3$Ge ohmic contacts demonstrate a $g_m$ of 145 mS/mm, considerably higher than found in the same devices with Ge/Pd and AuGeNi contacts.

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