Novel low-resistance ohmic contact to *n*-type GaAs using Cu_3Ge

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We show that ϵ_1-Cu_3Ge forms a low-resistance ohmic contact to *n*-type GaAs. The ϵ_1-Cu_3Ge contact exhibits a planar and abrupt interface and contact resistivity of 6.5×10^{-7} Ω cm^2 which is considerably lower than that reported for Ge/Pd and AuGeNi contacts on *n*-type GaAs with similar doping concentrations ($\sim1\times10^{17}$ 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. %. *n*-channel GaAs metal–semiconductor field-effect transistors using the ϵ_1-Cu_3Ge ohmic contacts demonstrate a higher transconductance compared to devices with Ge/Pd and AuGeNi contacts.

Alloyed AuGeNi contacts are the most commonly used ohmic contacts to *n*-type GaAs with a contact resistivity ρ_c, in the 10^{-6} Ω cm^2 range.[1] This metallization, however, often results in a nonplanar interface morphology[2,3] and the contacts are generally unstable when annealed at high temperatures due to the presence of the low melting point ($T_m\sim360$ °C) β-AuGa phase.[4] To improve the thermal stability of these eutectic-based AuGeNi contacts, low Au content NiGe(Au)W ohmic contacts have recently been developed.[5] However, these contacts exhibit a relatively high contact resistance after annealing at high temperatures (400 °C) as also do the In-based ohmic contacts.[6,7] To overcome the problems associated with the interface morphology of the alloyed contacts, ohmic contacts of a nonalloyed nature have been proposed[8] 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.[9] 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 resistivity.[9,10] In this letter, we report on a novel, more thermally stable, low-resistance ohmic contact to *n*-type GaAs using the ϵ_1-phase of Cu_3Ge. We have recently discovered that the ϵ_1 phase of Cu_3Ge which has a long-range ordered monoclinic crystal structure, exhibits a low metallic resistivity of ~6 $\mu\Omega$ cm at room temperature.[11] We also show that metal–semiconductor field-effect transistors (MESFETs) with the ϵ_1-Cu_3Ge ohmic contacts exhibit a considerably higher transconductance compared to devices that employ Ge/Pd and AuGeNi contacts.

The Cu_3Ge 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)$\times10^{17}$ 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_3Ge formation were determined assuming bulk density for Cu and Ge. The substrates were chemically cleaned in a solution of HCl:H_2O (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 $\sim1\times10^{-7}$ 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 $\sim5\times10^{-7}$ Torr. Electron diffraction measurements[12] showed that such an anneal is sufficient to form the ordered monoclinic ϵ_1 phase of Cu_3Ge ($a=0.2631$ nm, $b=0.4200$ nm, $c=0.4568$ nm, and $\gamma=89°$ 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_3Ge and the reaction with the GaAs substrate.

Standard photolithography was used to pattern the substrates for transmission line measurements[13] (TLM) and for MESFET devices with a *n*-type channel layer 0.3 μm thick doped to 3×10^{17} cm^{-3}. After patterning and etching mesa structures, source/drain contact windows were defined and the samples received the HCl:H_2O (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 ϵ_1-Cu_3Ge contacts to *n*-type GaAs (1×10^{17} cm^{-3}) at room temperature are linear. The contacts remain ohmic over the temperature range 300–50

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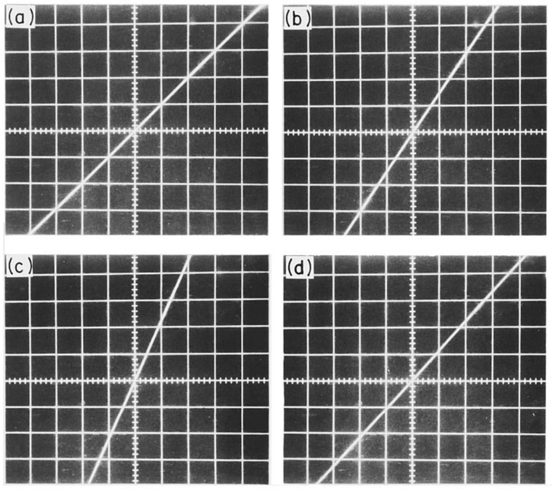

FIG. 1. $I-V$ characteristics at 300 K of contacts with (a) 25 at. % Ge, (b) 15 at. % Ge, and (c) 40 at. % Ge layers on n-type GaAs Si doped to 1×10^{17} cm^{-3}, formed at 400 °C for 30 min. (d) $I-V$ characteristics at 300 K of ϵ_1-Cu_3Ge contacts on p-type GaAs Zn doped to $\sim7\times10^{18}$ cm^{-3}. Scale: 10 mA/div vertical, 50 mV/div horizontal.

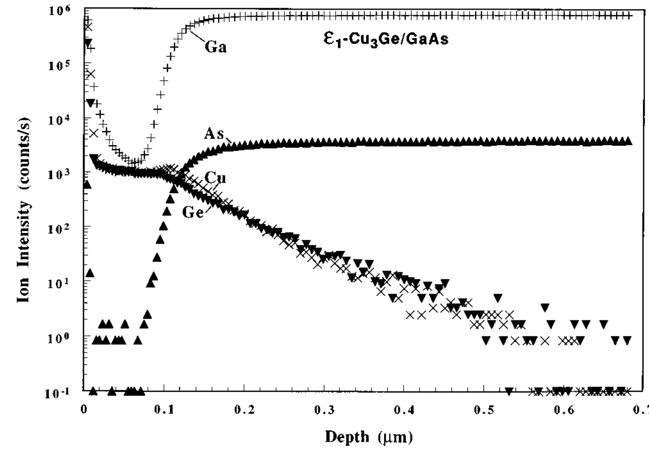

FIG. 2. SIMS profiles of an ϵ_1-Cu_3Ge/GaAs contact formed at 400 °C for 30 min. Note that only Ga has diffused into the ϵ_1-Cu_3Ge. The As signal in the ϵ_1-Cu_3Ge is at the background level.

K. Also, for contacts formed with Ge deposited first followed by the Cu layer the $I-C$ 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 ϵ_1-Cu_3Ge/GaAs system, no epitaxial Ge layer is detected and the ϵ_1-Cu_3Ge layer which exhibits a polycrystalline structure, is in contact with the GaAs substrate.[14] The interface between the ϵ_1-Cu_3Ge layer and the GaAs is planar and abrupt to within atomic dimensions ($\sim$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 measurements[12] showed that at 15 at. % Ge, the contact layer after annealing at 400 °C for 30 min consists entirely of the hexagonal close-packed ξ phase, while at 40 at. % Ge, it consists of the ϵ_1 phase (Cu_3Ge) and a small proportion of Ge (here the Ge grains are found to be epitaxial in nature[14]). 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 ξ and ϵ_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 ϵ_1-Cu_3Ge 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 ξ and ϵ_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 ϵ_1-Cu_3Ge/GaAs samples that Ga has diffused into the ϵ_1-Cu_3Ge, indicating that the Ga chemical potential in the ϵ_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 shown[15] 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 $D(T)=1.6\times10^{-5}\times\exp(-2.06/kT)$ 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 $\sim7\times10^{-21}$ 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 ϵ_1-Cu_3Ge contacts, as will be shown below, exhibit a remarkably low specific contact resistivity of 6.5×10^{-7} $\Omega\,cm^2$ 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-

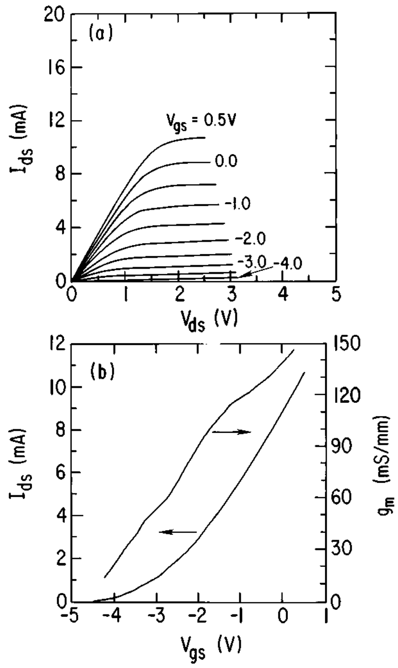

FIG. 3. (a) $I-V$ characteristics and (b) transconductance vs gate voltage characteristics at room temperature of an n-channel MESFET device with a gate length, a gate width, and a source-gate spacing of 1, 25, and 1 μm, respectively, using the ϵ_1-Cu_3Ge ohmic contacts.

alization of an ohmic contact on p-type GaAs due to acceptor compensation. The ohmic characteristics shown in Fig. 1(d) are not obtained unless the p-type substrate is highly doped to $\sim 7\times10^{18}$ cm^{-3}. More work on the dependence of ρ_c on doping concentration and temperature, however, is in progress to further clarify the picture.

The average contact resistance R_c of the ϵ_1-Cu_3Ge contact and the sheet resistance R_{sh} of the epitaxial layer (0.3 μm, $n=3\times10^{17}$ cm^{-3}) determined from TLM measurements at room temperature are 0.125 Ω mm and 237.5 $\Omega/\square$, respectively. This value of R_{sh} is in good agreement with that derived from Hall effect measurements. The average specific contact resistivity ρ_c calculated[21] from these data are 6.5×10^{-7} Ω cm^2, considerably lower than that reported for Ge/Pd (Ref. 10) and AuGeNi (Ref. 19) contacts on n-type GaAs with similar doping concentrations ($\sim 1\times10^{17}$ cm^{-3}) and for MBE-grown Ge ($n=8\times10^{19}$ cm^{-3})/GaAs ($n=1\times10^{17}$ cm^{-3}) contacts ($\sim 3\times10^{-6}$ Ω cm^2).[22] It should be emphasized here that regardless of whether Cu or Ge is initially in contact with the GaAs, the same value of ρ_c is obtained. Also, the contact resistivity is found to remain essentially unchanged after annealing at 450 °C for 2 h, in contrast to the Ge/Pd contacts.[9,10]

Figure 3 shows the $I-V$ characteristics and transconductance (g_m) versus gate voltage characteristics at room temperature for n-channel MESFET devices with the ϵ_1-Cu_3Ge contacts and a gate length and width of 1 and 25 μm, 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 ϵ_1-Cu_3Ge ohmic contacts to MESFET devices leads to a significant improvement in device performance.

In summary, we have shown that ϵ_1-Cu_3Ge forms a low-resistance ohmic contact ($\rho_c=6.5\times10^{-7}$ Ω cm^2) to n-type GaAs with doping concentrations of $\sim 1\times10^{17}$ 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 ϵ_1-Cu_3Ge 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 μm, respectively, using the ϵ_1-Cu_3Ge 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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