Low Resistance Ohmic Contacts to p-$Ge_{1-x}C_x$ on Si

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***Abstract*— We report on ohmic contact measurements of Al, Au, and W metallizations to p-type epitaxial $Ge_{0.9983}C_{0.0017}$ grown on a (100) Si substrate by molecular beam epitaxy (MBE). Contacts were annealed at various temperatures, and values of specific contact resistance have been achieved which range from $10^{-5}\ \Omega\cdot cm^2$ to as low as $5.6\times10^{-6}\ \Omega\cdot cm^2$. Theoretical calculations of the contact resistance of metals on $Ge_{1-x}C_x$ with small percentages of carbon, based on the thermionic field emission mechanism of conduction, result in good agreement with the experimental data. We conclude that Al and Au are suitable ohmic contacts to p-$Ge_{0.9983}C_{0.0017}$ alloys.**

I. INTRODUCTION

INVESTIGATION of Group IV alloys has been attracting more attention recently [1]. Previous Group IV alloy work has focused upon the use of lattice mismatched $Si_{1-x}Ge_x$ alloys on Si substrates to enhance device performance [2]. However, the $Si_{1-x-y}Ge_xC_y$ ternary alloy exhibits adjustable bandgaps while allowing the lattice constant to be varied from compressively to tensially strained about the Si lattice matching condition. For this reason, renewed attention has shifted to the $Si_{1-x-y}Ge_xC_y$ [3] and $Ge_{1-x}C_x$ [4] material systems. Mostly this research has centered upon material properties, but very recent reports have discussed $Ge_{1-x}C_x$ p-n [5] and $Si_{1-x-y}Ge_xC_y$ p-i-n [6] diodes. Related to device issues, the quality of the ohmic contacts need to be investigated.

Ohmic contacts are of great importance and an essential part of all solid-state device fabrication. No ohmic contact measurement to $Ge_{1-x}C_x$ alloys has been reported yet, however, and little work has been published for ohmic contacts on pure Ge either. The work reported here concentrates on Ge-rich $Ge_{1-x}C_x$ cubic heterostructures grown on Si by molecular beam epitaxy (MBE). In this paper, we present the first experimental results of metallization of the pure metals Al, Au, and W on epitaxial p-type $Ge_{1-x}C_x$ on Si for use as low resistance ohmic contacts.

II. EXPERIMENTS

The $Ge_{1-x}C_x$ epilayer was grown by solid source MBE in an EPI 620 system [7]. The substrate was (100) oriented n-type Si with a carrier concentration of 10^{15} cm^{-3}. The substrate temperature during growth was kept constant at 400 °C. The total thickness of the $Ge_{1-x}C_x$ epilayer was measured to be 0.6 μm. The $Ge_{1-x}C_x$ epilayer was doped p-type by a concurrent boron flux, using a third effusion cell loaded with pure boron in a pyrolytic graphite crucible. The Ge-rich layer was confirmed to be single crystal by X-ray analysis, but was relaxed as confirmed by transmission electron microscopy (TEM). From Hall effect measurements, the electrically active B concentration was about 4×10^{18} cm^{-3}, which was almost 100% activation, by comparing to the B concentration from secondary ion mass spectrometry (SIMS) measurements. The carbon concentration was 0.17%, as determined by the growth condition, calibrated from higher C concentrations.

Ohmic contacts to the p-type $Ge_{0.9983}C_{0.0017}$ were measured using the standard transmission line method (TLM) [8]. The TLM mesa patterns were fabricated by first defining rectangular GeC regions by photolithography and then etching the unprotected regions down to the Si substrate, using a H_3PO_4:H_2O_2:H_2O (1:6:3) etchant solution [9]. After degreasing, the contact area was defined by standard liftoff technology. Some samples received a brief etch prior to deposition, to remove about 300 Å of material and subsequent surface contamination. Al and Au contacts were evaporated thermally and by electron beam, respectively, while W contacts were magnetron sputtered. Each contact pad in the TLM pattern was 80 μm × 80 μm. The samples were then cleaved into smaller specimens, and underwent separate heat treatments at various temperatures in an annealing furnace under a forming gas (15% H_2–N_2) ambient. The annealing furnace consisted of a resitively heated graphite stage with a thermocouple embedded into the block. All annealing times were 3 min, the minimum response time of the annealing station, to achieve shallow ohmic contacts. Shallow contacts are needed for devices, such as bipolar transistors, to avoid diffusing through a p-n junction below.

III. RESULTS AND DISCUSSION

Fig. 1 shows a plot of the total resistance R_T measured between metal contacts as a function of the contact spacing between them. Three parameters, sheet resistance (ρ_s), contact resistance (R_c), and transfer length (L_T), were extracted from a least-squares interpolation line of the data. Assuming that the sheet resistance of the $Ge_{1-x}C_x$ epilayer outside the contact area (ρ_s) is the same as that beneath the contact area (ρ_{sc}), the total resistance is given by,

$$R_T=\frac{\rho_s d}{Z}+2R_c\approx\frac{\rho_s d}{Z}+2\frac{\rho_s L_T}{Z}\qquad(1)$$

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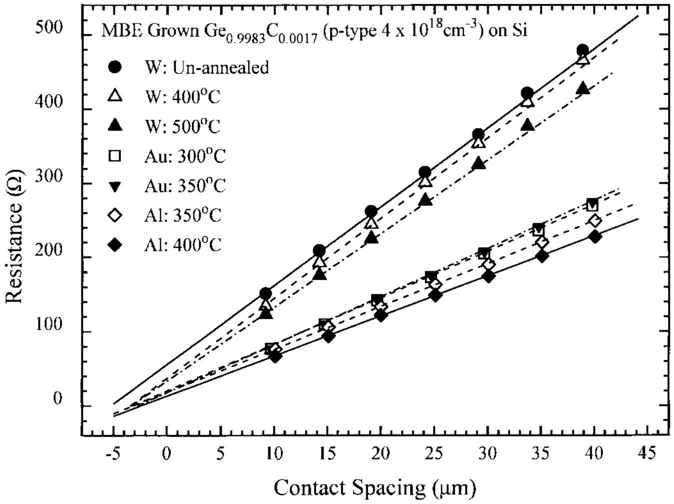

Fig. 1. The total resistance R_T measured between various metal contact pads in the TLM structure as a function of the contact separation for p-$Ge_{0.9983}C_{0.0017}$ on Si.

TABLE I

SPECIFIC CONTACT RESISTANCES EXTRACTED FROM THE DATA SHOWN IN FIG. 1 OF Al, Au, AND W METALS TO p-$Ge_{0.9983}C_{0.0017}$ ON Si UNDER VARIOUS ANNEAL TEMPERATURES

Contact Metal	Annealing Temperature (°C)	Specific Contact Resistance ρ_c (Ω·cm²)
W	un-annealed	4.9×10^{-5}
W	400	2.0×10^{-5}
W	500	1.7×10^{-5}
Au	300	8.2×10^{-6}
Au	350	5.6×10^{-6}
Al	350	1.2×10^{-5}
Al	400	6.5×10^{-6}

where d is the contact spacing and Z is the contact width. The values of specific contact resistance, as shown in Table I, were calculated from these parameters.

Our results demonstrate low resistance ohmic contacts for Al and Au on $Ge_{0.9983}C_{0.0017}$, with values of specific contact resistance of the order of $10^{-5} - 10^{-6}$ $\Omega\cdot cm^2$, after suitable annealing. For the 300 °C anneal temperature, the Al contacts were found to be under-annealed, in which the plot of R_T versus d was an irregular scatter instead of a straight line. When the annealing temperature was raised to 450 °C or above, strong reactions of both Al and Au with the $Ge_{0.9983}C_{0.0017}$ epilayer occurred, which resulted in a highly irregular morphology with numerous metallic islands.

Optimal anneal temperatures based on resistances for Al and Au occurred within this temperature window, between these two extremes. The lowest contact resistances achieved were 6.5×10^{-6} $\Omega\cdot cm^2$ for Al at a 400 °C annealing temperature and 5.6×10^{-6} $\Omega\cdot cm^2$ for Au at 350 °C.

In spite of its higher contact resistance, tungsten was also explored as a nonalloyed contact and under heat treatment conditions. The W–GeC specific contact resistance was still on the order of 10^{-5} $\Omega\cdot cm^2$, even for an unannealed sample. The W contacts showed excellent adhesion to the $Ge_{0.9983}C_{0.0017}$, with a smooth surface even after successive temperature steps up to 650 °C. This indicated the low reactivity of W with GeC.

We consider three current transport mechanisms for a metal-semiconductor interface: thermionic emission (TE), thermionic field emission (TFE), and field emission (FE). The conduction of a metal-semiconductor contact is determined by the energy barrier height at the interface (Φ_B), the doping concentration near the semiconductor surface (N), the effective mass of the semiconductor majority charge carriers (m^*), the dielectric constant of the semiconductor (ϵ_s) and the temperature (T). Comparisons are given to the Mead rule using the Bardeen approximation [10], Tersoff's metal-induced gap states (MIGS) model [11], Tersoff's model based on a gap center and an adjustable parameter related to the metal electronegativity [12], and Cardona and Christensen's dielectric midpoint energy (DME) model [13].

The $Ge_{1-x}C_x$ alloy is expected to be covalently bonded and therefore have barrier heights independent of the metal work function for metals with weak chemical bonding. This is supported by the similar measured values of the specific contact resistance for Au and Al. Although it is known that barrier heights depend somewhat on the metal through its electronegativity [14], the agreement of contact resistances for Al and Au signifies a lack of dependence of barrier height upon type of metal, indicating that perhaps surface states and defects at the interface dominate.

To determine the conduction mechanism for the Au–GeC and Al–GeC (with small percentage of carbon) systems, we assumed Ge properties for the GeC alloy in the following calculation. This assumption is based on the small percentage of carbon used in this $Ge_{1-x}C_x$ study. For bulk Ge with a doping level of 4×10^{18} cm^{-3}, kT/E_{00} is 1.6, where

$$E_{00} = \frac{q\hbar}{2}\sqrt{\frac{N}{\epsilon_s m^*}} \tag{2}$$

is a characteristic energy. Based on this value of E_{00}, we expect the TFE mechanism to dominate, and the specific contact resistance can be calculated by [15], [16]

$$\rho_c = \frac{k}{qA^*T}\frac{kT}{\sqrt{\pi(\Phi_B + u_F)E_{00}}}\cosh\frac{E_{00}}{kT}\sqrt{\coth\frac{E_{00}}{kT}} \times \exp\left[\frac{\Phi_B + u_F}{E_0} - \frac{u_F}{kT}\right] \tag{3}$$

where A^* is the Richardson constant, u_F is the difference between the Fermi level and the valence band in semiconductor, and

$$E_0 = E_{00}\coth\frac{E_{00}}{kT}. \tag{4}$$

The values of specific contact resistance from the theoretical calculations, by using Mead, both Tersoff, and DME models

TABLE II

SPECIFIC CONTACT RESISTANCES FROM MEASUREMENTS AND THEORETICAL CALCULATIONS OF Al AND Au TO p-$Ge_{0.9983}C_{0.0017}$ ON Si

Metal	**Specific Contact Resistance ρ_c ($\Omega\cdot cm^2$)**					
	Our Data	**Theoretical Values**				
		Mead[10]	**Tersoff (E_B)**[11]	**Tersoff (adjusted)**[12]	**DME**[13]	**Other**[17]
Au	5.6×10^{-6}	6.4×10^{-6}	1.8×10^{-6}	9.7×10^{-8}	5.3×10^{-8}	7.6×10^{-8}
Al	6.5×10^{-6}	6.4×10^{-6}	1.8×10^{-6}		5.3×10^{-8}	1.8×10^{-6}

for the barrier height, are listed in Table II, and compared with our experimental data. As a comparison, values of specific contact resistance calculated from other workers' data [17] of barrier heights are also listed. The theoretical values impose a lower limit upon the ohmic contact measurements. Those theoretical values from Mead rule and Tersoff's effective midgap energy are very consistent with the experimental results obtained, while that from DME model gives a much lower limit.

Due to the high melting point of W, the heat of reaction of W-GeC is relatively large compared to Au or Al. This can be seen from our experiments by the fact that no morphological reaction was observed even after an anneal at 650 °C. It was expected that W could form a Schottky barrier on GeC due to the difference between the W work function and the electron affinity of $Ge_{1-x}C_x$ using small carbon percentages. However, reasonable ohmic contacts were achieved in this system. This is actually expected because the sputtering process which deposited the W metal probably produced defects sites near the semiconductor surface, thereby increasing the interface states density and lowering the barrier height.

IV. CONCLUSION

In conclusion, based on an industry standard of $10^{-5}\,\Omega\cdot\mathrm{cm}^2$ [18], suitable low resistance ohmic contacts to p-$Ge_{0.9983}C_{0.0017}$ epitaxial layers grown on Si substrates using pure metallic contacts have been achieved. The contacts studied used Al, Au, and W metals. The metals Al and Au resulted in the lowest contact resistance of $6.5\times10^{-6}\,\Omega\cdot\mathrm{cm}^2$ and $5.6\times10^{-6}\,\Omega\cdot\mathrm{cm}^2$, respectively. The W metal also achieved reasonable results despite its low reactivity. Analysis implies a thermionic field emission model for the contact resistance.

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