Regrown ohmic contacts to thin GaAs layers and two-dimensional electron gas

A. Palevski, P. Solomon, T. F. Kuech, and M. A. Tischler
IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598

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We report on the first realization of extremely low resistivity regrown ohmic contacts to a variety of GaAs/AlGaAs structures using selective epitaxy. For planar regrown n^+-GaAs contacts to n-GaAs we have obtained contact resistivity values $\sim 1\times10^{-7}\ \Omega\ \mathrm{cm}^2$, and $\sim 1\times10^{-8}\ \Omega\ \mathrm{cm}^2$ for lateral contacts to a 10-nm-thick buried n^+-GaAs layer. The contact resistances were substantially temperature independent from 77 to 300 K. Regrown contacts to a 2DEG structure exhibited a much higher and temperature-dependent contact resistivity which could be accounted for (according to numerical simulation) by $\sim 5\times10^{12}\ \mathrm{cm}^{-2}$ traps at the AlGaAs/ regrown GaAs interface. Post-growth annealing of the regrown interface drastically reduced the value of contact resistivity for 2DEG structures to $\sim 2\times10^{-8}\ \Omega\ \mathrm{cm}^2$.

The ability to grow GaAs epitaxially onto a previously processed, patterned GaAs wafer can play a crucial role in the design of the future devices. We have recently demonstrated that the trap concentration at the regrown interfaces grown by metalorganic vapor phase epitaxy (MOVPE) utilizing a conventional[1] or $(C_2H_5)GaCl$[2,3] based growth chemistry together with appropriate pregrowth chemical preparation, can be as low as $N_T \sim 10^{11}\ \mathrm{cm}^{-2}$. We have determined that low-resistance regrown electrical contacts to GaAs structures are tolerant to the presence of a much higher trap concentration than $\sim 10^{11}\ \mathrm{cm}^{-2}$. Details of the MOVPE technique, developed for making selective epitaxial growth, have been published[3] with further details on the regrowth techniques used in preparation of our samples given elsewhere.[2] Electrical resistivities of contacts obtained using this technique for one specific interface geometry, the nonpatterned planar contact, have also been presented.[2]

We report here on the results obtained on regrown edge contacts to thin GaAs layers and to 2DEG (two-dimensional electron gas) structures. The results of numerical simulations modeling these structures are also presented. We give additional results on planar contacts and their analytical analysis. Both the analysis of data for the lateral contacts using the numerical simulations and the analysis of data for the planar contacts, discussed in this letter, provide information on the quality of the regrown interface. The low values of contact resistivities reported in this letter suggest that the regrown interfaces are relatively free of chemical and structural imperfections which could trap carriers.

The relationship between the trap concentration N_T and contact resistivity ρ_c can be illustrated through the following example. Consider a layer of n^+-GaAs epitaxially regrown on a surface of n-doped GaAs (Fig. 1). Solving Poisson's equation under the assumption of a degenerate electron energy distribution, we can estimate the height of the potential barrier, Φ, due to the presence of the traps at the regrown interface:

$$\Phi = \frac{eN_T^2}{2\epsilon n^+} - \frac{3}{5e}E_F, \qquad (1)$$

where e is the electron charge, ϵ is the dielectric constant, and E_F is the Fermi energy. Two conduction mechanisms could be important depending on the size of Φ and the temperature, thermionic emission, and/or tunneling. Both mechanisms of conduction through a Schottky type barrier and the resistances associated with it are well established.[4] The formulae given by Padovani and Stratton in Ref. 4 (valid for $\Phi > E_F/4e$) approximately predict the value of the contact resistivity for the simple geometry of a planar regrown contact for a given concentration of traps. Using formula (29) of Ref. 4 for tunneling to analyze our results at 300 K we find that the contact resistivity $\rho_c < 2\times10^{-7}\ \Omega\ \mathrm{cm}^2$ for a $n^+ = 6\times10^{17}\ \mathrm{cm}^{-3}$ layer regrown on an $n = 2\times10^{17}\ \mathrm{cm}^{-3}$ substrate is consistent with $\Phi < 20$ meV or, from Eq. (1), N_T must be less than $4\times10^{11}\ \mathrm{cm}^{-2}$. Using formula (3) from the same reference, valid for low temperatures, we get similar estimates of both Φ and N_T. This indicates that the contact resistivity of the regrown GaAs layer for such parameters of the structure and interface barrier should be temperature independent, as we measured.

The geometry and structures of the samples studied here are shown schematically in Fig. 2. For the study of the planar contacts [Fig. 2(a)], the regrowth was performed on unpatterned wafers. Two wafers that contained 200 nm n^+-GaAs layer doped with Si to $3.0\times10^{18}\ \mathrm{cm}^{-3}$ under a 200 nm n layer of GaAs doped with Si to $2\times10^{17}\ \mathrm{cm}^{-3}$ were slightly chemically etched in order to imitate the processes involved in patterning. Two different dopant elements were used in the regrown GaAs layers: Si $\sim 1.5\times10^{18}\ \mathrm{cm}^{-3}$ or Sn $\sim 1\times10^{19}\ \mathrm{cm}^{-3}$. The regrown layers were 200 nm thick for both wafers. After the regrowth, the layers were patterned using standard reactive ion etching techniques to produce the samples for testing electrical properties of contacts. We used the transmission line method (TLM)[5] to measure contact resistivity. The length of the contacts was 6 μm and the separation between them varied from 1 to 6 μm in steps of 1.5 μm. The width of the transmission line was 20 μm. Approximately 30–50 transmission lines were measured for each structure. The correlation coefficient of these structures was greater than 0.9995, implying a uniform geometry of the lines and homogeneity of the contact resistivities on a given transmission line structure. These measurements pro-

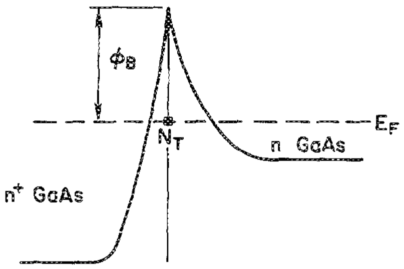

FIG. 1. Schematic potential diagram of a contact between a regrown layer (n^+-GaAs) and an n-GaAs layer with a concentration of traps, N_T, at the interface.

vide an estimate of contact resistance R_c and the sheet resistance of the transmission line $R_\square$. The average values of these quantities measured at 300 and 77 K are summarized in Table I. The relative error of the data is 10%. The values of contact resistivities for Sn-doped contacts are somewhat higher due to an initial doping transient which resulted in a lower doping concentration near the regrown interface. This problem was later resolved when the regrowth was applied to edge contacts. The value of the transfer length defined as $L_T = R_c/R_\square$ is much shorter than the length of the contact, as required by the transmission line method. It should be noted that contact resistivity ρ_c is defined from the theory of transmission line techniques as $\rho_c = R_c^2/R_\square$. ρ_c includes the contribution of separately measured AuGeNi alloy contact to the regrown layer ρ_M and a contribution from the n layer. The contact resistivity of the n layer, ρ_{cn}, is established analytically using the value of bulk resistivity ρ_{bn}: $\rho_{cn} = \rho_{bn} t_n$, where t_n is the thickness of the n layer. According to formula (1) and the formulae in Ref. 4, the results in Table I imply that the number of traps at the regrown interface should be $N_T \simeq 4\times 10^{11}$ cm^{-2}, in agreement with published data.[1,2]

The structures shown in Figs. 2(b) and 2(c) were fabricated to test lateral regrown contacts. Wafers containing a thin n^+ layer of GaAs doped to 3×10^{18} cm^{-3} and a 2DEG with electron density $n = 7\times 10^{11}$ cm^{-2} were patterned in the form of a transmission line. The contact areas on the transmission line first were etched 50 nm deeper than the conducting layer and later refilled by n^+-GaAs. Growth occurred selectively within the contact areas using a SiN layer as a mask.[3] Two types of dopants were again used in the regrown layers, Si: $\sim 3\times 10^{18}$ cm^{-3} and Sn $\sim 1\times 10^{19}$ cm^{-3}. The results of TLM studies on these structures are summarized in Table II. As in the case of planar contacts, the resistance of the lateral contact to a narrow channel of n^+-GaAs for both types of dopants in the regrown layer is very low. The mean standard deviation of the measured values of R_c

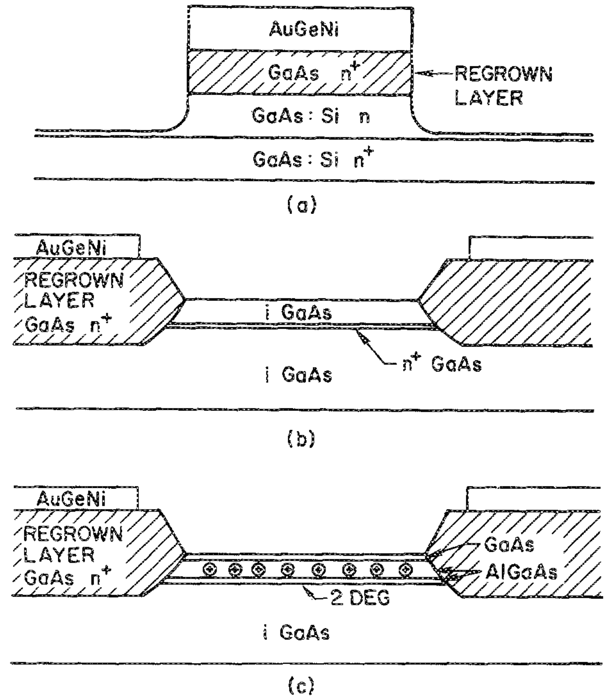

FIG. 2. Schematic view of the fabricated structures (a) regrown contact to n^+/n layers of GaAs, (b) lateral regrown contact to an n^+-GaAs narrow channel, (c) lateral regrown contact to 2DEG.

given in Table II (excluding 2DEG data) is estimated to be $\sim 1\times 10^{-3}$ Ω cm. The presented results are rounded to a half of a significant digit. If we assume that the cross-sectional area of the contact is given by the thickness of the n^+ layer, ~ 10 nm, a contact resistivity of $\rho = 4\times 10^{-9}$ Ω cm^2 is calculated from our measurements. The contact resistance is temperature independent for this structure. This result is consistent with the absence of the barrier at the regrown interface. The situation is quite different on the 2DEG structure. The large and temperature-dependent contact resistivity indicates that there is an enhanced concentration of traps at the interface between the 2DEG and regrown layer relative to the two cases discussed above. It is quite plausible that the proximity of theAlGaAs surface to the contact area could contribute to high contact resistance. The number of traps at the surface of theAlGaAs could be much larger than at the GaAs surface due to the presence of an Al-rich oxide.

We used a computer simulation[6] to investigate the electrical properties of contacts to the GaAs/AlGaAs heterojunction including the effect of interface traps. Figure 3 shows a potential diagram and contours of the carrier density obtained from the numerical solution of the two-dimensional Poisson equation for the lateral contact of an n^+ re-

TABLE I. TLM data on the vertical regrown contacts (structure A).

Type of dopant	$T = 300$ K					$T = 77$ K				
	$R_\square$ (Ω/□)	R_c (Ω cm)	L_T (μm)	ρ_c (Ω cm^2)	ρ_c' (Ω cm^2)[a]	$R_\square$ (Ω/□)	R_c (Ω cm)	L_T (μm)	ρ_c (Ω cm^2)	ρ_c' (Ω cm^2)[a]
Si	60	5×10^{-3}	0.8	4.2×10^{-7}	1.5×10^{-7}	55	4.5×10^{-3}	0.8	3.7×10^{-7}	1.0×10^{-7}
Sn	55	6.5×10^{-3}	1.1	7.7×10^{-7}	5×10^{-7}	50	8×10^{-3}	1.6	1.3×10^{-6}	1.0×10^{-6}

[a] $\rho_c' = \rho_c - \rho_M - \rho_{cn}$, where $\rho_c = R_c^2/R_\square$, $\rho_M = 9\times 10^{-8}$ Ω cm^2 (measured), $\rho_{cn} = \rho_{bn} t_n = 1.8\times 10^{-7}$ Ω cm^2, $t_n = 2\times 10^{-5}$ cm, $\rho_{bn} = 9\times 10^{-3}$ Ω cm (textbook).

TABLE II. TLM data on the lateral regrown contacts (structures B and C).

Type of structure and dopant	$T = 300$ K $R_{\square}$ ($\Omega/\square$)	R_c (Ω cm)	ρ_c (Ω cm^2)[a]	$T = 77$ K $R_{\square}$ ($\Omega/\square$)	R_c (Ω cm)	ρ_c (Ω cm^2)[a]
lateral B:Si	625	4×10^{-3}	4×10^{-9}	625	4×10^{-3}	4×10^{-9}
lateral B:Sn	870	4.5×10^{-3}	4.5×10^{-9}	870	4.5×10^{-3}	4.5×10^{-9}
2DEG C:Si[b]	1250	4×10^{-1}	4×10^{-7}	···	4	4×10^{-6}
2DEG C:Sn[b]	900	1.5×10^{-1}	1.5×10^{-7}	···	4×10^{-1}	4×10^{-7}
2DEG annealed C:Sn	1250	2×10^{-2}	2×10^{-8}	860	2×10^{-2}	2×10^{-8}

[a] $\rho_c = R_c w$, where $w = 1\times10^{-6}$ cm.
[b] I-V curve of the contact is nonlinear; value of contact resistance is given for 1 μA/μm.

grown layer to an AlGaAs/GaAs heterojunction for different sidewall slopes: (a) normal and (b) 45° of regrown interface. We used $N_{T1} = 5\times10^{12}$ cm^{-2} as the number of traps at the interface between the regrown layer and AlGaAs and $N_{T2} = 5\times10^{11}$ cm^{-2} as the number of traps at the interface between the regrown layer and GaAs for both geometries presented in Fig. 3. The numerical studies indicate that a $N_{T1} \simeq 5\times10^{12}$ cm^{-2} at the interface of the regrown GaAs layer with AlGaAs would deplete the 2DEG at the corner of the contact with regrown GaAs in the sloped sidewall case [Fig. 3(b)] resulting in a high value of the contact resistivity, whereas having a 90° vertical sidewall [Fig. 3(a)] would greatly reduce the contact resistivity. The slope of the sidewall obtained from the isotropic chemical etching used in our experiment is expected to be close to 45°. The calculated contact resistivity for this case, shown in Fig. 3(b), is similar to the results observed in our experiment. It also follows from the computer simulations that the contact resistance could be reduced significantly if the contact to the 2DEG layer is moved about 20 nm away from the corner of AlGaAs. Practically, this requires diffusion of dopants from

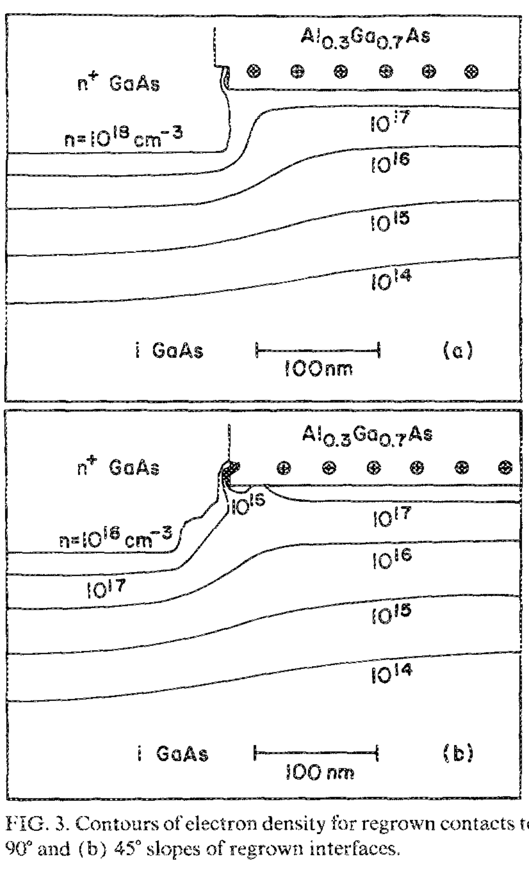

FIG. 3. Contours of electron density for regrown contacts to 2DEG for (a) 90° and (b) 45° slopes of regrown interfaces.

the regrown GaAs layer laterally into the 2DEG region. We have attempted such a diffusion on the 2DEG samples regrown with an Sn-doped GaAs layer. Sn possesses a high diffusion coefficient relative to Si. We annealed the samples at 850 °C for 20 min and then measured their contact resistivities. As predicted by the simulations the contact resistivity becomes very small and temperature independent (see Table II). The average is determined with 25% relative errror. Although the study of the Sn diffusion in the lateral dimension is incomplete, we can estimate the Sn diffusion distance of ~100 nm.

Our contact resistivities are sufficiently low that a comparison to the limiting contact resistance in the absence of any barrier becomes relevant. Assuming that the transport region, namely, the length of the n layer, is shorter than the mean free path in this region, yet larger than the carrier spill over region from the n^+ layer, the contact resistance in the limit of vanishing applied voltage is found to be $\rho_{c,\min} = m\cdot\bar{v}/e^2n$. This follows from the simple argument that the current flow is limited by the average thermal velocity $\bar{v}$ for a nondegenerate electron gas. In the case of a degenerate electron gas, $m\cdot\bar{v}$ should be replaced by the Fermi momentum P_F. This resistance is equivalent to the Sharvin resistance[7] for a degenerate electron gas. Using a typical value of $\bar{v} = 2\times10^7$ cm s^{-1}, minimum contact resistivities of $\sim5\times10^{-8}$ Ω cm^2 for $n = 1\times10^{17}$ cm^{-3} and $\sim2.5\times10^{-9}$ Ω cm^2 for $n = 2\times10^{18}$ cm^{-3} are derived. The experimentally determined contact resistivities for vertical structures as well as lateral contacts to thin layers and two-dimensional electron gases are quite close to these fundamental limits. The excellent electrical characteristics of these contacts, coupled with the selective nature of the growth, should have many useful applications in a wide range of devices.

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[1] T. F. Kuech, E. Marshall, G. J. Scilla, R. Potemski, C. M. Ransom, and M. Y. Hung, J. Cryst. Growth 77, 539 (1986).
[2] M. A. Tischler, T. F. Kuech, A. Palevski, and P. Solomon, Appl. Phys. Lett. (unpublished).
[3] T. F. Kuech, M. A. Tischler, and R. Potemski, Appl. Phys. Lett. **54**, 910 (1989).
[4] For tunneling, see F. A. Padovani and R. Stratton, Solid-State Electron. **9**, 695 (1966); for thermal emission, see S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), pp. 254–259.
[5] H. H. Berger, Solid-State Electron. **15**, 145 (1972).
[6] J. Y.-F. Tang and S. E. Laux, IEEE Trans. Computer-aided Design **CAD-5** (4), 645 (1986).
[7] Yu. V. Sharvin, Zh. Exptl. Theoret. Phys. **48**, 986 (1965) [Sov. Phys. JETP **21**, 655 (1965)].