Electrical characteristics of regrown interfaces using diethylgallium chloride-based metalorganic vapor phase epitaxy

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The electrical characteristics of regrown interfaces deposited using an alternate metalorganic chemistry, diethylgallium chloride (DEGaCl), are investigated. With the appropriate HCl pre-regrowth surface treatment, these interfaces are found to be of very high quality with no substantial interface charge. The contact resistivity, as determined by transmission line measurements, is $(2–4)\times 10^{-7}\ \Omega\ \text{cm}^2$ at both 77 and 300 K. Secondary-ion mass spectroscopy measurements show no detectable accumulation of impurities at the regrown interface, in contrast to those regrown using the conventional trimethylgallium-based chemistry.

There have been many studies investigating the growth of epitaxial material upon processed semiconductor surfaces.[1–8] In general, these regrown interfaces are dominated by the presence of interfacial contaminants and structural disorder, which can result in traps or excess charge. Interfacial traps or charge lead to a potential barrier at these interfaces which impede the current transport across the interface. In addition, traps lead to undesirable effects such as backgating in field-effect transistor structures.[9] Molecular beam epitaxy,[1,2] halide and hydride vapor phase epitaxy,[3,4] and metalorganic vapor phase epitaxy[5–8] (MOVPE) have all been used in such studies. Many approaches to the preparation and growth of these interfaces have also been examined.[1–8,10,11] From these studies, both the growth technique and the pregrowth treatment have been found to be important in achieving high quality electrical interfaces. In the case of MOVPE, the use of the common growth precursors such as trimethylgallium [TMG or $Ga(CH_3)_3$] and AsH_3 can produce regrown interfaces with moderate concentrations of interfacial charge. The MOVPE studies have also investigated the use of *in situ* vapor etching procedures which improve the electrical characteristics of the regrown interfaces. These Cl- or BI-based etches do, however, require high-temperature treatments[5–7,10,11] which can degrade the device structures through interdiffusion and dopant redistribution.

We have developed an alternative growth chemistry based on diethylgallium chloride[12–14] [$(C_2H_5)_2GaCl$ or DEGaCl] which leads to very high quality interfaces free from substantial interface charge. This growth chemistry also produces selective epitaxy when used in conjunction with patterned substrates.[12,13] The ability to selectively grow high quality interfaces has several interesting applications in both submicron devices as well as a variety of novel optoelectronic and three-dimensional integrated structures. In order to achieve high quality interfaces, we have investigated a variety of pregrowth treatments in conjunction with the DEGaCl growth chemistry. The use of a HCl oxide removal step was found to be crucial in producing electrically clean interfaces. The electrical characteristics of these interfaces are examined using capacitance-voltage (*C-V*) profiling, temperature-dependent transport measurements, and contact resistivity measurements. Secondary-ion mass spectroscopy (SIMS) is used to examine any impurity accumulation near the regrown interface.

All structures used in these experiments consisted of GaAs grown using DEGaCl and AsH_3 on a previously prepared substrate. The substrates for regrowth were prepared by first growing a GaAs layer with conventional MOVPE, using TMG, AsH_3, and disilane (Si_2H_6), on an n^+ substrate, oriented (100), 2° towards ⟨011⟩. This was followed by the preregrowth chemical treatment, described below. All growths were done on unmasked substrates, with the post-growth patterning performed lithographically. The growth temperature and pressure were 650 °C and 78 Torr and the AsH_3 mole fraction was 8×10^{-3}. DEGaCl was introduced into the reactor by bubbling 400 sccm of H_2 through the bubbler held at 47 °C with a pressure of 90 Torr. H_2 was also used as the carrier gas with a flow of 7.4 ℓpm. Intentional n-type doping with Si_6H_6 was used only in structure B. Additional details of the growth process have been previously reported.[12]

Initial studies were carried out to examine the effect of preregrowth surface treatments on the transport characteristics of the regrown interface contained in structure A, shown in Fig. 1(a). Lightly doped layers were used to facilitate detection of any potential barrier to carrier transport across the regrown interface. The light doping reduces the tunneling component of the current which could mask a small potential barrier. Three preregrowth treatments were applied to the sample prior to the growth of the top contact. These were (1) as-grown (AG), i.e., no treatment; (2) organic clean (OR), ultrasound in acetone and isopropyl alcohol for 5 min each, water rinsed, and blown dry with N_2; and (3) OR + HCl, solvent cleaned as in (2) followed by 5 min of ultrasound in 100% HCl, water rinsed, and blown dry with N_2. The regrown layer was deposited simultaneously on substrates with different pretreatments.

Front contacts 500 μm in diameter were isolated by mesa etching. Traditional Au/Ge/Ni metallurgy was used for ohmic contacts on both the front and back. The current-voltage (*I-V*) characteristics of the regrown contacts were examined as a function of temperature from 12 to 300 K. Room-temperature capacitance-voltage (*C-V*) measurements on unprocessed layers were used to examine the carrier profile near the regrown interface.

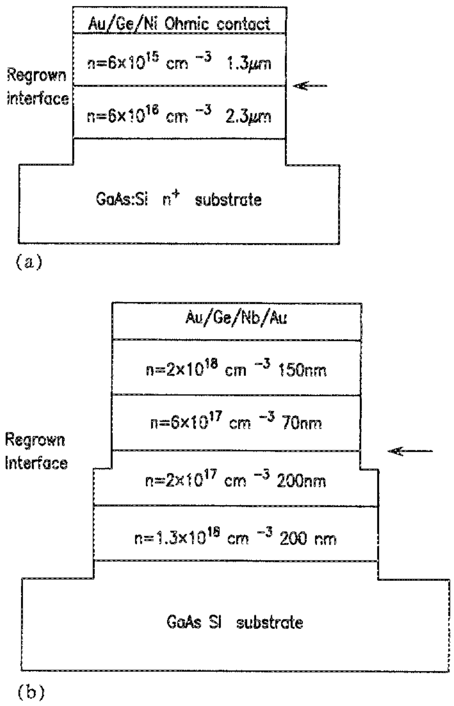

FIG. 1. (a) Structure A for transport measurements; (b) structure B for contact resistivity measurements.

The contact resistivity of the regrown interface was measured on a second structure B, shown in Fig. 1(b). Structure B utilizes heavier doped layers which reduces the bulk resistance, permitting a lower contact resistance to be measured. Two preregrowth treatments were examined. The first was OR + HCl, which, as will be discussed below, was found to give the best results in the initial study on structure A. The second treatment included a phosphoric acid based etch which is commonly used to etch both GaAs and (Al,Ga)As. This would allow the extension of this work to (Al,Ga)As-based heterostructures. This treatment, PHOS + HCl, included a 100 Å etch in H_3PO_4: H_2O_2:H_2O 2:1:50 followed by 30 s in 100% HCl, water rinsed, and blown dry in N_2.

Transmission line patterns were fabricated on isolated mesas. Front ohmic contact was made using Au/Ge/Nb/Ni/Au to prevent penetration of the metallurgy through the regrown interface.[15] The contacts were 6 by 20 μm with nominal spacings of 1.0 to 5.5 μm in 1.5 μm steps. The contact resistance was measured using the transmission line method[16] (TLM) at 300 and 77 K. The contact resistivity of the metal-n^+ interface was also measured.

The I-V characteristics for structure A with AG, OR, and OR + HCl treatments measured at 300 and 13 K are shown in Fig. 2. All measurements at 300 K indicate ohmic behavior with symmetric characteristics for positive and reverse bias. At 13 K, AG and OR + HCl pretreatments again had linear characteristics as seen at 300 K, but with a slight increase in slope, indicating a drop in resistance. The OR sample exhibited a slightly rectifying characteristic at 13 K. These rectifying characteristics are not symmetric, which is a consequence of the doping profile of the structure, and is consistent with thermionic emission as the dominant current conduction mechanism.

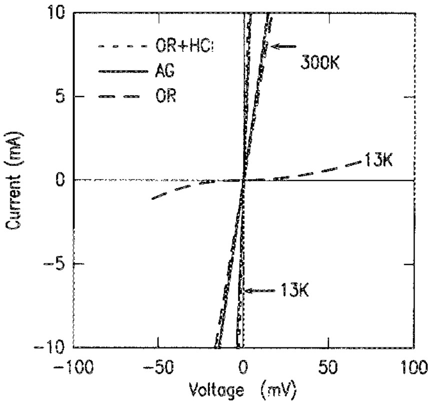

FIG. 2. I-V measurements at 300 and 13 K for structure A with three different preregrowth treatments.

Carrier concentration profiles for these structures, as determined by C-V profiling, are shown in Fig. 3. The OR + HCl structure exhibits a smooth transition through the regrown region, with no evidence of any trap-induced charge at the regrown interface. In this structure, interface traps, depending on their occupancy, can result in a peak at the interface, a dip just before the interface, or both. These effects are seen in both the AG and OR structures, indicating the presence of traps at the regrown interfaces. The peak in the AG structure corresponds to an interfacial trap density of about 1.4×10^{11} cm^{-2}. The lowest detectable trap concentration measurable in this structure is $\simeq 1.5\times10^{10}$ cm^{-2}. Therefore, the trap level in the OR + HCl structure is below 1.5×10^{10} cm^{-2}.

Table I lists values for the measured contact resistivity ρ_C^* and sheet resistance $R_\square$ of the transmission line at 77 and 300 K for the preregrowth treatments PHOS + HCl and OR + HCl. The values are averages for many structures using only measurements with a correlation coefficient greater than 0.999. The contact resistivity of the Au/Ge/Nb/Au metallurgy to the regrown layer ρ_M was measured separately and is 8.9×10^{-8} Ω cm^2. An additional resistance component is that of the GaAs(2×10^{17} cm^{-3}) just below the regrown interface. This contribution to the total measured resistivity can be estimated using $\rho_{CN} = \rho_N \times d_N$, where ρ_{CN}

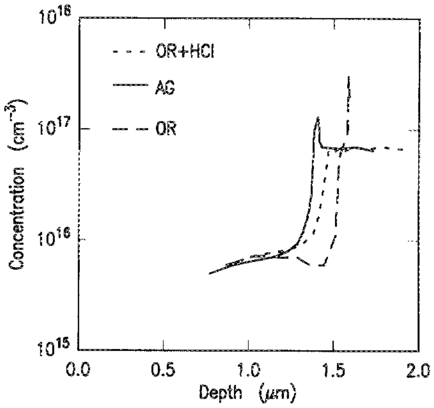

FIG. 3. Carrier concentration vs depth determined by C-V profiling for structure A with three different preregrowth treatments.

TABLE I. Contact resistivity of regrown interfaces measured on structure B.

Treatment	Temperature (K)	No. Meas.	$R_{\square}$ ($\Omega/\square$)	$\rho_c^* \times 10^{-7}$ (Ω cm^2)	$\rho_c \times 10^{-7}$ (Ω cm^2)
OR + HCl	300	22	60.5	6.6	3.9
OR + HCl	77	15	53.8	5.6	2.9
PHOS + HCl	300	24	60.4	5.0	2.3
PHOS + HCl	77	23	55.5	4.9	2.2

is the contact resistivity of the n layer under the contact, ρ_N is the resistivity of the n layer ($\simeq 9 \times 10^{-3}$ Ω cm 300 K), and d_N is the thickness of the n layer. This gives a value of 1.8×10^{-7} Ω cm^2 for ρ_{CN}, using 200 nm for d_N. These parasitic components have been subtracted from the measured value to get the actual contact resistivity of the regrown interface ρ_C, also listed in Table I.

The transport and capacitance-voltage measurements show that the OR + HCl pretreatment yields the best electrical characteristics. These include linear I-V behavior and the absence of any appreciable trap concentration at or near the regrown interface. The OR structure has rectifying I-V characteristics at low temperatures while both the OR and AG structures have traps at the regrown interface as determined from C-V measurements. The presence of traps at this interface is not surprising in light of previous results using conventional TMG-based growth. These indicated that, irrespective of preregrowth treatments, appreciable trap concentrations, 2×10^{11} to $> 3 \times 10^{12}$ cm^{-2}, are often observed at the regrown interface.[5] In the present work, the maximum trap density is only $\simeq 1.4 \times 10^{11}$ cm^{-2}. These electrical characteristics are confirmed by SIMS profiling which, on a sample treated with PHOS + HCl prior to regrowth, gave no evidence of an accumulation of Si, C, or O at the interface. This is in contrast to regrowth using TMG where large impurity spikes are almost always seen at the regrown interface.[5,7]

The contact resistivity of the regrown interface is very low, on the order of $(2\text{–}4) \times 10^{-7}$ Ω cm^2. These values are at the limit of the accuracy of this technique. Thus, the small differences between pregrowth treatments are not considered significant. The contact resistivities remain unchanged at 77 K, which is another indication that a barrier, if present at this interface, is very small. This confirms the initial results that the DEGaCl-based chemistry, combined with an HCl pretreatment, yields a very clean regrown interface.

The improvement found in the regrown interfaces is attributed to the use of a HCl pregrowth treatment together with the DeGaCl-based growth chemistry. HCl is known to remove the surface oxide from GaAs. Removal of this oxide layer from the growth surface may "lift-off" surface contaminants resulting from any previous processing step. The DeGaCl growth precursor probably decomposes to GaCl at or near the surface of the growing layer. The presence of Cl on the surface may serve to remove the common impurities such as Si and C from the growth front. These results are somewhat surprising in view of the past literature on regrown interfaces. Previous work on the inorganic-based growth of GaAs, in which GaCl and As$_2$ or As$_4$ are used as growth nutrients, indicates that there are large concentrations of impurities at these regrown interfaces.[3] Both HCl as a pregrowth treatment and GaCl as a growth constituent have been previously used in such regrowth studies without achieving the high quality interfaces presented here.[3,5] The chemical nature of the *in situ* cleaning which must be taking place within the MOVPE growth environment is, therefore, still unknown.

In conclusion we have demonstrated that regrown GaAs interfaces, using DEGaCl-based chemistry and an HCl preregrowth treatment, have excellent electrical characteristics. These electrical characteristics, in combination with the selective nature of the DEGaCl-based growth chemistry, have many potential device applications. We are currently investigating such selectively grown structures, including self-aligned regrown contacts to field-effect transistors and two-dimensional electron gases. The regrown interfaces are characterized by the absence of traps and ohmic or linear I-V characteristics over a wide temperature range of 13–300 K. Transmission line measurements give a very low value of contact resistivity of $(2\text{–}4) \times 10^{-7}$ Ω cm^2. This value does not change for temperatures as low as 77 K. SIMS measurements indicate the absence of any appreciable impurity accumulation at the regrown interfaces. This chemical cleanliness, resulting from the HCl-based preregrowth treatment and the DEGaCl-based growth, leads to these electrical results which represent a significant improvement over other conventional MOVPE regrowth techniques.

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