Ohmic nanocontacts to GaAs using undoped and *p*-doped layers of low-temperature-grown GaAs

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The development and characterization of high-performance nanocontacts to *n*-GaAs are reported. The nanocontacts can be made to both undoped and *p*-doped low-temperature-grown GaAs (LTG:GaAs) cap layers. The geometry of the nanocontact is well characterized and requires the deposition of a 4 nm single-crystalline Au cluster onto an ohmic contact structure which features a chemically stable LTG:GaAs surface layer prepared using an *ex situ* chemical self-assembly technique. A self-assembled monolayer of xylyl dithiol ($HS-CH_2-C_6H_4-CH_2-SH$) is required to provide mechanical and electronic tethering of the Au cluster to the LTG:GaAs surface. For the case of an undoped LTG:GaAs cap layer, a specific contact resistance of $1\times10^{-6}\,\Omega\,cm^2$ and a current density of $1\times10^{6}\,A/cm^2$ have been measured from scanning tunneling microscopy. When a *p*-doped LTG:GaAs cap layer is used, the corresponding values are $1\times10^{-7}\,\Omega\,cm^2$ and $1\times10^{7}\,A/cm^2$, respectively. Improved surface stability as evidenced by a lower oxidation rate for *p*-doped LTG:GaAs provides a natural explanation for the higher-quality ohmic contact properties of the nanocontact to the *p*-doped LTG:GaAs cap layer. © *2000 American Institute of Physics.* [S0003-6951(00)03002-3]

As reported earlier, nonalloyed ohmic contacts are potentially useful for nanodevice applications since they are free from a deep interface and they possess high spatial uniformity.[1] Low resistance nonalloyed contacts to *n*-GaAs can be realized by employing a surface layer of low-temperature-grown GaAs (LTG:GaAs), i.e., GaAs grown at a temperature of 250–300 °C by molecular beam epitaxy.[2] Large area *ex situ*, nonalloyed ohmic contacts employing a chemically stable LTG:GaAs surface layer can provide a specific contact resistance (ρ_c) below $1\times10^{-6}\,\Omega\,cm^2$.[3] A nanometer scale contact with comparable performance has also been demonstrated.[1]

In this study, we extend the previous work to the development and characterization of high performance nanocontacts to *n*-GaAs using both undoped (*n*-type) and *p*-doped LTG:GaAs cap layers. A model explaining the difference in the contact properties between the samples is proposed.

To assess the differences between the contact behavior to *n*-GaAs using undoped and *p*-doped LTG:GaAs cap layers, two wafers were prepared with similar vertical structures except for the doping in the LTG:GaAs cap layer (Be doped at $2\times10^{20}\,cm^{-3}$ for the *p*-doped case). The large density of midgap states in LTG:GaAs pins the bulk Fermi level within a few tenth of an eV above midgap, regardless of the doping level.[2] The controlled-geometry nanocontact was obtained by depositing a 4 nm single crystalline Au cluster onto the LTG:GaAs based ohmic contact structure using *ex situ* chemical self-assembly techniques. A self-assembled monolayer[4] of xylyl dithiol ($HS-CH_2-C_6H_4-CH_2-SH$) denoted as XYL) provides mechanical and electronic tethering of the Au cluster to the LTG:GaAs surface. Details of the semiconductor layer structure and the nanocontact fabrication have been presented previously.[1]

A separate ellipsometric study of XYL-coated LTG:GaAs indicated that the XYL-coated LTG:GaAs is a stable surface even under air exposure.[1] It is believed that the sulfur to GaAs bond provides passivation comparable to that observed in studies involving elemental sulfur, with additional stability provided both by the characteristics of the LTG:GaAs and the organic tail of the XYL molecule.[5–7] A patterned XYL layer has been used as an etch mask for wet chemical etching of the GaAs layers by covering these molecules on a certain area of the sample surface.[8]

A ultrahigh vaccum (UHV) scanning tunneling micros-

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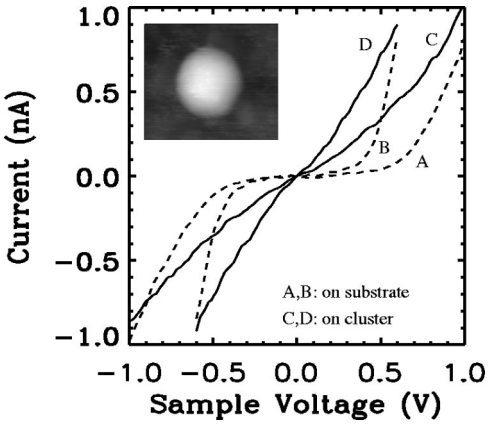

FIG. 1. $I-V$ data taken with the tip positioned over the XYL-coated substrate (dashed) and over the Au cluster (solid) with $I_{set}=0.8$ nA and -1.0 V (A and C), -0.6 V (B and D) for V_{set}. Inset picture is a 20×20 nm STM topographic image of Au cluster tethered to the XYL-coated LTG:GaAs, acquired with $I_{set}=1.0$ nA and $V_{set}=-1.0$ V.

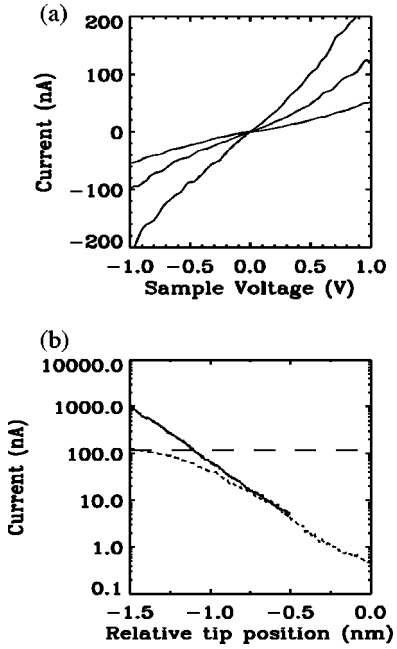

FIG. 2. (a) $I-V$ data from a Au cluster acquired with $I_{set}=50$ nA (A), 100 nA (B), and 200 nA (C) and $V_{set}=-1.0$ V. (b) $\log(I)$ vs relative tip position above Au cluster, at constant $V_{set}=-1.0$ V for undoped LTG:GaAs cap layer (dotted line) and for p-doped cap layer (solid line). The initial separation corresponding to $I_{set}=0.5$ nA and 3.0 is plotted at zero and at -0.5 nm for undoped and p-doped LTG:GaAs, respectively.

copy (STM) was used to locate and probe the electronic properties of the nanocontacts. Figure 1 shows a series of measured current–voltage ($I-V$) relationships for cases where the STM tip was positioned over a Au cluster (curves C, D) and over the XYL-coated LTG:GaAs surface (A, B). When $I-V$ was measured over a Au cluster, the data exhibited an ohmic behavior with a significant enhancement in the conduction for low bias voltages compared to $I-V$ data over the XYL-coated substrate, regardless of the dopant type of LTG:GaAs cap layer.

The ohmic behavior is found to persist to higher tunnel currents. When an undoped LTG:GaAs cap layer is probed, ohmic $I-V$ characteristics were observed up to ~30 nA when the tip is positioned over a Au cluster.[1] When $I-V$ measurements were attempted at larger current levels, the STM tip was observed to dislodge the Au cluster. For these high currents, the STM tip comes so close to the cluster that it mechanically damages the nanocontact. For the case of a p-doped cap layer, the ohmic behavior persists to higher tunnel currents (up to 200 nA) without damaging the Au cluster, as shown in Fig. 2(a).

In order to determine ρ_c and set realisitic limits on the maximum current capability of the nanocontact, a technique measuring I versus the tip-cluster spacing $[I(z)]$ is preferable.[1] If the tip contacts the cluster, the tip-to-cluster resistance is expected to become negligible, so the current will saturate at a value dictated by the resistance between the cluster and the semiconductor substrate. The latter resistance is the contact resistance for the nanocontact. Figure 2 (b) is the plot of $I(z)$ obtained with the tip positioned over a ~4-nm-high Au cluster on undoped LTG:GaAs (dotted line) and p-doped LTG:GaAs (solid line) which have been passivated by the organic XYL layer.

In this plot, the initial height of the tip above the cluster was set by specifying an I_{set} and V_{set}; negative values for the relative tip position represents tip motion towards the sample. Data for the p-doped sample was shifted by 0.5 nm to account for difference in initial heights due to different set conditions. The ρ_c of this ohmic contact can be estimated due to the well-characterized, single crystalline Au clusters used in this study. From geometrical considerations, the area $\mathcal{A}$ of a Au(111) facet on a ~4-nm-high, truncated octahedral cluster is $\sim9\times10^{-14}$ cm^2. Therefore the ρ_c can be found from

$$\rho_c \simeq (V/I_{sat})\mathcal{A}. \tag{1}$$

The values of ρ_c determined from the above $I-V$ measurements provide an upper limit for the contact resistance of these contacts because there may still be a non-negligible component of resistance due to the tip-cluster gap.

The data from the undoped LTG:GaAs cap layer (dotted line) in Fig. 2 (b) was discussed in the previous study.[1] From the saturation current I_{sat} (dashed horizontal line; 100 nA), a $\rho_c\simeq1\times10^{-6}\,\Omega$ cm^2 and a maximum current density $J_{max}\simeq1\times10^6$ A/cm^2 were determined for this nanocontact. Compared with undoped LTG:GaAs, a p-doped LTG:GaAs cap layer [solid curve in Fig. 2 (b)] does not show a saturation effect. Instead, the $\log(I)$ vs z relationship remained roughly linear up to 1000 nA, the measurement limit of our system. This means that the tip is still not in close contact to the cluster surface. Using the maximum current (1000 nA) for the p-doped LTG:GaAs capped sample, we determined an upper bound for ρ_c of $\sim1\times10^{-7}\,\Omega$ cm^2 and a lower bound for J_{max} of $\sim1\times10^7$ A/cm^2.

A quantitative conduction model has been developed recently for the metal-semiconductor ohmic contact structure employing LTG:GaAs.[9] The model can be extended to the nanocontact case by considering the XYL as a thin layer of a leaky dielectric between the cluster and the semiconductor layers. A small resistance due to tunneling between the Au cluster and the GaAs conduction band requires a small surface barrier at the semiconductor interface. Several experiments provide evidence for the control of this surface barrier by the XYL and LTG:GaAs layers, and provide evidence for

a reduced barrier height in *p*-doped LTG:GaAs when compared to the undoped layer. This is qualitatively in agreement with our data.

For example, Holden *et al.*[10] studied the surface band bending of thick *n*- and *p*-doped LTG:GaAs surface layers without XYL. Following prolonged air exposure, the *n*-doped LTG:GaAs layer showed midgap surface Fermi level pinning. The band bending in *p*-doped LTG:GaAs is still *n* type (upward band bending) as a consequence of the large number of donor-like defects, but it was nearly flat, indicating a reduced surface-state (charge) density in the *p*-doped LTG:GaAs. X-ray photoemission spectroscopy (XPS) measurements of undoped LTG:GaAs indicate that the time constant for significant oxidation of the surface is longer than one hour at atmosphere.[11] During nanocontact fabrication, the surface oxide is stripped using HCl immediately before the sample is coated with XYL. It is believed that this oxide strip temporarily restores the surface Fermi level to an unpinned condition. The prompt deposition of the XYL monolayer in a dry nitrogen glovebox appears to provide passivation against significant reoxidation. Our ellipsometry measurements also indicate an improved stability of *p*-doped over undoped LTG:GaAs. This indicates an improved surface stability, i.e., less oxidation and fewer surface states, for the *p*-doped LTG:GaAs. The reduced surface state density in *p*-doped LTG:GaAs corresponds to a lower barrier height for electron tunneling, and therefore a reduced contact resistance. In addition to the barrier height difference, midgap states in LTG:GaAs layer can also affect the overall conduction. Feenstra *et al.*[12] observed a peak of midgap states below the Fermi level in *n*-doped LTG:GaAs and double peaks straddling the Fermi level in *p*-doped LTG:GaAs. Any states around the Fermi level in *p*-doped LTG:GaAs can contribute to conduction. Taken together, these factors can explain the better ohmic contact performance of the *p*-doped LTG:GaAs capped sample.

In conclusion, we have developed and characterized a nanometer scale, ohmic contact to *n*-GaAs using Au cluster/XYL/GaAs structure. Au clusters are found to be well tethered to the LTG:GaAs substrate by a monolayer of XYL molecules. The $I-V$ characteristics of the Au cluster/XYL/GaAs nanocontact exhibit an ohmic behavior regardless of the dopant type. For the case of an undoped LTG:GaAs cap layer, a ρ_c of $\sim 1\times 10^{-6}\,\Omega\,\mathrm{cm}^2$ and a $J_{\max}$ of $\sim 1\times 10^{6}\,\mathrm{A/cm}^2$ have been measured from UHV STM current-voltage spectroscopy. When a *p*-doped LTG:GaAs cap layer is used, the corresponding values are $\sim 1\times 10^{-7}\,\Omega\,\mathrm{cm}^2$ and $\sim 1\times 10^{7}\,\mathrm{A/cm}^2$, respectively. The difference in the contact properties between the samples can be qualitatively explained by the better surface stability of *p*-doped LTG:GaAs and the presence of midgap states near the Fermi level. Although the focus of the present work has been to characterize the electronic properties of the nanocontact, a similar approach, i.e., a molecularly uniform, low-dielectric insulator which controls the surface potential, should also be useful for realizing low resistance large area contacts.

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