Ex situ Ohmic contacts to *n*-InGaAs

Ashish Baraskar[a)]
Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, California 93106

Mark A. Wistey
Department of Electrical Engineering, University of Notre Dame, Notre Dame, Indiana 46556

Vibhor Jain, Evan Lobisser, Uttam Singisetti, and Greg Burek
Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, California 93106

Yong Ju Lee
Technology Manufacturing Group, Intel Corporation, Santa Clara, California 95054

Brian Thibeault
Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, California 93106

Arthur Gossard
Department of Electrical and Computer Engineering and Materials Department, University of California, Santa Barbara, Santa Barbara, California 93106

Mark Rodwell
Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, California 93106

(Received 22 February 2010; accepted 24 May 2010; published 19 July 2010)

The authors report ultralow specific contact resistivity (ρ_c) in *ex situ* Ohmic contacts to *n*-type $In_{0.53}Ga_{0.47}As$ (100) layers, with an electron concentration of 5×10^{19} cm^{-3}. They present the ρ_c obtained for molybdenum (Mo) contacts to *n*-type $In_{0.53}Ga_{0.47}As$, with the semiconductor surface cleaned by atomic H before metal deposition. The authors compare these data with the ρ_c obtained for contacts made without atomic H cleaning. After exposure to air during normal device processing, the semiconductor surface was prepared by UV-ozone exposure plus a dilute HCl etch and subsequently exposed to thermally cracked H. Mo contact metal was deposited in an electron beam evaporator without breaking vacuum after H cleaning. Transmission line model measurements showed a contact resistivity of $(1.1\pm0.9)\times10^{-8}$ Ω cm^2 for the $Mo/In_{0.53}Ga_{0.47}As$ interface. This ρ_c is equivalent to that obtained with *in situ* Mo contacts [$\rho_c=(1.1\pm0.6)\times10^{-8}$ Ω cm^2]. *Ex situ* contacts prepared by UV-ozone exposure plus dilute HCl (without any atomic H exposure) result in $\rho_c=(1.5\pm1.0)\times10^{-8}$ Ω cm^2. © *2010 American Vacuum Society.* [DOI: 10.1116/1.3454372]

I. INTRODUCTION

Very low resistance metal-semiconductor contacts are required for submillimeter-wave electronics; III-V bipolar and field-effect transistors require a specific contact resistivity (ρ_c) of less than 1×10^{-8} Ω cm^2 to achieve simultaneous 1.5 THz current-gain (f_t) and power gain ($f_{\max}$) cutoff frequencies.[1,2] Contact resistivity strongly depends on semiconductor surface preparation prior to metal deposition.[3] *In situ* metal deposition immediately after semiconductor growth avoids surface oxidation and contamination, and contact resistivity (ρ_c) as low as $(1.1\pm0.6)\times10^{-8}$ Ω cm^2 has been so obtained.[4] But, transistor fabrication process flows often require that contacts be formed after the semiconductor has been exposed to air. To obtain low contact resistivity with such *ex situ* contacts, surface preparation requires considerable attention. Ti/Pt/Au contacts deposited on Ar^+ sputtered *n*-InGaAs result in $\rho_c=4.3\times10^{-8}$ Ω cm^2.[5] $\rho_c=4.1\times10^{-8}$ Ω cm^2 (after correcting for metal resistance) was obtained with TiW contacts to *n*-InGaAs; in those samples the semiconductor surface was oxidized with UV generated ozone and subsequently treated with dilute HCl prior to metal deposition.[3]

III-V semiconductor surfaces contaminated by oxides and carbon compounds can also be cleaned by atomic H.[6] After exposure to atomic H, atomically clean GaAs surfaces have been confirmed with reflection high energy electron diffraction (RHEED).[7,8] Atomic H has been used to clean surfaces prior to semiconductor regrowth[9] by molecular beam epitaxy (MBE). Atomic H cleaning is carried out at lower temperatures than conventional thermal oxide desorption and hence causes less surface roughening due to less group V desorption. While thermal cleaning under group V flux is usually carried out at 550 °C for InP (100) and InGaAs (100), and 580 °C for GaAs (100), surface cleaning with atomic H can be achieved at 390 °C for these semiconductors.[10,11] How-

[a)]Electronic mail: ashish.baraskar@ece.ucsb.edu

ever, considerable surface indium loss has been observed after prolonged atomic H cleaning of InGaAs alloys.[11]

We here report ρ_c for *ex situ* Mo contacts to *n*-type $In_{0.53}Ga_{0.47}As$, with an electron concentration of 5×10^{19} cm^{-3}. We studied two surface cleaning techniques: one involving UV-ozone/HCl treatment and the other involving UV-ozone/HCl/H treatment. We compare the ρ_c obtained for these two techniques.

II. EXPERIMENT

The experiments used three vacuum chambers connected under ultrahigh vacuum (UHV), the first containing a H cracking cell and a substrate heater, the second containing the RHEED system used for surface characterization, and the third containing an electron beam evaporator for metal deposition.

The semiconductor epilayers were grown by a Gen II solid source MBE system. A 150 nm undoped $In_{0.52}Al_{0.48}As$ layer was grown on a semi-insulating InP (100) substrate, followed by 100 nm of silicon (Si) doped $In_{0.53}Ga_{0.47}As$. The samples were grown at a 420 °C substrate temperature with a 1400 °C Si cell temperature. The active carrier concentration, mobility, and sheet resistance were obtained from Hall measurements by placing indium (In) contacts on samples. The samples were removed from vacuum for a long period (395 days); this permits the surface to oxidize, as would occur during normal device processing. The samples were then exposed to UV-ozone for 30 min and then treated with 1:10 HCl: H_2O and de-ionized (DI) water rinse for 1 min each. The samples were then immediately loaded into the vacuum chamber. On a first set of samples, without breaking vacuum, 20 nm of Mo was deposited in an electron beam evaporator without any further surface treatment. A second set of samples was exposed to thermally cracked H for times ranging from 20 to 40 min and temperatures ranging from 375 to 420 °C. The filament temperature of the H cracking cell was maintained at 2200 °C. The chamber pressure during H cleaning was maintained at 10^{-6} torr. RHEED patterns were recorded along the [110] and $[\bar{1}10]$ azimuths after H cleaning. The samples were then transferred to the electron beam evaporator where 20 nm Mo was deposited.

To extract the specific contact resistivity, the samples were processed into TLM structures.[12] For the TLM structures (Fig. 1), Ti (20 nm)/Au (500 nm)/Ni (50 nm) contact pads were patterned using optical photolithography and liftoff after an e-beam deposition. The Au layer is 500 nm thick to reduce interconnect resistance. Mo was then dry etched in a SF_6/Ar plasma using Ni as an etch mask. The TLM structures were then isolated using mesas formed by photolithography and a subsequent wet etching with $1:1:25:H_3PO_4:H_2O_2$:DI water. A scanning electron microscope (SEM) image of the TLM pattern is shown in Fig. 2.

Resistances were measured using a four-point (Kelvin) probe technique on an Agilent 4155C semiconductor parameter analyzer.[4] In the Kelvin probing structure (Fig. 2), the observed resistance, $R_{measured}=2\rho_c/WL_T+\rho_s L_{gap}/W+R_{metal}$, contains a small contribution R_{metal} from the sheet resistivity

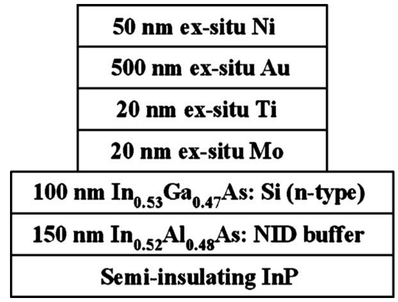

FIG. 1. Cross-section schematic of the metal-semiconductor contact layer structure used for contact resistivity (ρ_c) measurements.

(ρ_m/T_m) of the contact metal. Here ρ_c is the metal-semiconductor contact resistivity, ρ_s is the semiconductor sheet resistivity, $L_T=\sqrt{\rho_c/\rho_s}$ is the transfer length, ρ_m is the bulk metal resistivity, and T_m is the contact metal thickness. The dimensions W and L_{gap} are defined in Fig. 2. R_{metal} is determined from separate measurements of ρ_m/T_m and from numerical finite-element analysis of the contact geometry. R_{metal} changes the contact resistivity data by less than 5% for TLM structures with $W=25$ μm.

The sheet resistance of the semiconductor between the contacts does not change after being exposed to SF_6/Ar plasma etch for removing Mo.[4] This validates the extraction of the contact resistivity (ρ_c) from the observed lateral access resistivity (ρ_H) and semiconductor sheet resistivity (ρ_s).

III. RESULTS AND DISCUSSION

A diffuse (1×1) RHEED pattern was observed on samples without any H clean. As the samples were exposed to atomic H and the exposure time and temperature are increased, a gradual improvement from a (1×1) to a (2×4) reconstruction was observed. Figure 3 shows the RHEED patterns recorded along the [110] and $[\bar{1}10]$ azimuths after 40 min of atomic H exposure at 420 °C. The observed (2×4) reconstruction indicates an As-rich or As-terminated surface.[11,13,14]

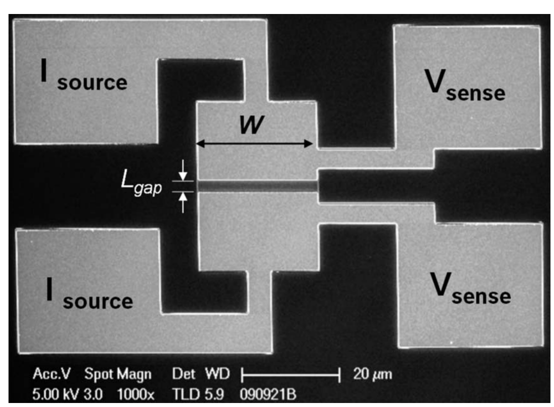

FIG. 2. SEM image of the TLM pattern used for the contact resistivity (ρ_c) measurement. Separate pads were used for current biasing and voltage measurement.

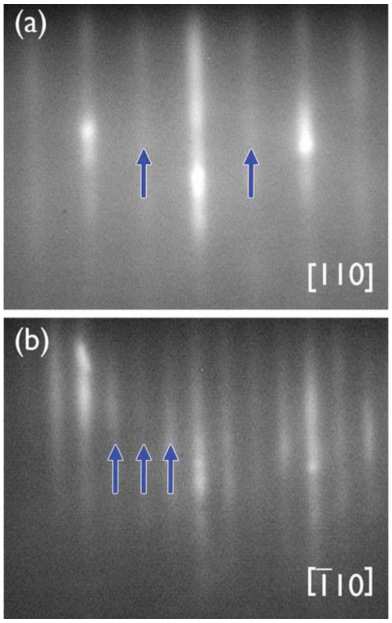

FIG. 3. (Color online) RHEED patterns of the atomic H cleaned sample along the [110] and [$\bar{1}$10] azimuths showing (2×4) reconstructed surface.

Figure 4 shows the variation of TLM test structure resistance with contact separation for samples with different surface treatments. From the TLM data, $\rho_c=(1.1\pm 0.9)\times 10^{-8}$ and $(1.5\pm 1.0)\times 10^{-8}$ Ω cm^2 were determined for samples with UV-ozone/HCl/H treatment and UV-ozone/HCl treatment, respectively. The contact resistivity here obtained is the lowest reported to date for *ex situ* contacts to *n*-type $In_{0.53}Ga_{0.47}As$ and is comparable to $(1.1\pm 0.6)\times 10^{-8}$ Ω cm^2 obtained for *in situ* Mo contacts to *n*-type $In_{0.53}Ga_{0.47}As$.[4]

For the TLM structures, the transfer length was found to be 280 nm, 2.8:1 larger than the N+ layer thickness; hence, the resistance analysis assuming that one-dimensional current flow is appropriate.[15] Hall measurements on the samples indicate an active carrier concentration, a mobility, and a sheet resistance of 4.8×10^{19} cm^{-3}, 984 cm^2/V s, and 13 Ω, respectively. The sheet resistance obtained with TLM measurements was 13.5 Ω, which closely correlates with the sheet resistance obtained with Hall measurement.

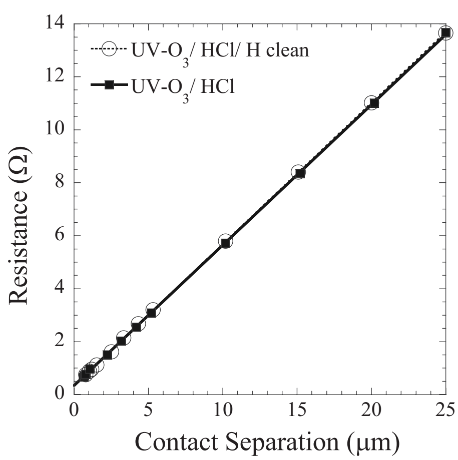

FIG. 4. Measured TLM resistance as a function of contact separation for *ex situ* molybdenum Ohmic contacts to *n*-$In_{0.53}Ga_{0.47}As$.

In separate experiments, samples doped at $\sim 5\times 10^{19}$ cm^{-3} were exposed to air for 2, 36, and 395 days, and treated with UV-ozone/HCl/H. Mo was deposited and TLM structures were fabricated on these samples. Observed ρ_c were 1.1, 1.1, and 1.0 Ω μm^2, respectively. A separate set of samples, doped at $\sim 5\times 10^{19}$ cm^{-3}, exposed to air for 2 and 395 days, was treated with UV-ozone/HCl. Mo contacts were formed and TLM structures were fabricated on these samples. Observed ρ_c were 1.4 and 1.5 Ω μm^2, respectively. These data indicate that the duration of air exposure has little effect on ρ_c given the surface preparation procedures employed.

IV. CONCLUSIONS

In summary, we report ultralow contact resistivity with *ex situ* contacts to heavily doped *n*-type $In_{0.53}Ga_{0.47}As$. The contact resistivities obtained with UV-ozone/HCl cleaned and UV-ozone/HCl/H cleaned contacts were $(1.5\pm 1.0)\times 10^{-8}$ and $(1.1\pm 0.9)\times 10^{-8}$ Ω cm^2, respectively. The contact resistivity obtained here is comparable to that obtained with *in situ* Mo contacts, suggesting the effective removal of surface contaminants. These ultralow resistance *ex situ* Mo contacts make them a potential candidate to be applied in highly scaled HBTs and other devices of near-terahertz bandwidths.

[1]M. J. W. Rodwell, M. L. Le, and B. Brar, Proc. IEEE **96**, 271 (2008).
[2]M. J. W Rodwell *et al.*, Proceedings of the IEEE Compound Semiconductor Integrated Circuit Symposium, 2008.
[3]Vibhor Jain, Ashish K. Baraskar, Mark A. Wistey, Uttam Singisetti, Zach Griffith, Evan Lobisser, Brian J. Thibeault, Arthur C. Gossard, and Mark. J. W. Rodwell, 21st IEEE International Conference on Indium Phosphide and Related Materials, 2009 (unpublished), pp. 358–361.
[4]Ashish Baraskar, Mark A. Wistey, Vibhor Jain, Uttam Singisetti, Greg Burek, Brian Thibeault, Yong Ju Lee, Arthur Gossard, and Mark Rodwell, J. Vac. Sci. Technol. B **27**, 2036 (2009).
[5]G. Stareev, H. Künzel, and G. Dortmann, J. Appl. Phys. **74**, 7344 (1993).
[6]G. R. Bell, N. S. Kaijaks, R. J. Dixon, and C. F. McConville, Surf. Sci. **401**, 125 (1998).
[7]T. Sugaya and M. Kawabe, Jpn. J. Appl. Phys., Part 2 **30**, L402 (1991).
[8]A. Khatiri, J. M. Ripalda, T. J. Krzyzewski, G. R. Bell, C. F. McConville, and T. S. Jones, Surf. Sci. **548**, L1 (2004).
[9]U. Singisetti *et al.*, IEEE Electron Device Lett. **30**, 1128 (2009).
[10]T. Kikawa, I. Ochiai, and S. Takatani, Surf. Sci. **316**, 238 (1994).
[11]F. S. Aguirre-Tostado, M. Milojevic, C. L. Hinkle, E. M. Vogel, R. M. Wallace, S. McDonnell, and G. J. Hughes, Appl. Phys. Lett. **92**, 171906 (2008).
[12]H. H. Berger, Solid-State Electron. **15**, 145 (1972).
[13]W. Braun, *Applied RHEED: Reflection High-Energy Electron Diffraction During Crystal Growth* (Springer, Germany, 1999).
[14]P. A. Bone, J. M. Ripalda, G. R. Bell, and T. S. Jones, Surf. Sci. **600**, 973 (2006).
[15]E. G. Woelk, H. Krautle, and H. Beneking, IEEE Trans. Electron Devices **33**, 19 (1986).