Interfacial reactions of Pt-based Schottky contacts on InGaP

L. H. Chu, E. Y. Chang, Y. H. Wu, J. C. Huang, Q. Y. Chen, W. K. Chu, H. W. Seo, and C. T. Lee

Citation: Applied Physics Letters **92**, 082108 (2008); doi: 10.1063/1.2834849
View online: http://dx.doi.org/10.1063/1.2834849
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/92/8?ver=pdfcov
Published by the AIP Publishing

Interfacial reactions of Pt-based Schottky contacts on InGaP

L. H. Chu,[a] E. Y. Chang,[b] Y. H. Wu, and J. C. Huang
Department of Materials Science and Engineering, National Chiao-Tung University, Hsinchu 30050, Taiwan, Republic of China

Q. Y. Chen[c] and W. K. Chu
Department of Physics and Texas Center for Superconductivity, University of Houston, Houston, Texas 77204, USA

H. W. Seo
Department of Physics, University of Arkansas, Little Rock, Arkansas 72204, USA

C. T. Lee
Institute of Microelectronics, National Cheng-Kung University, Tainan 70101, Taiwan, Republic of China

(Received 7 March 2007; accepted 3 December 2007; published online 28 February 2008)

We have investigated the interfacial reaction between platinum and InGaP in a Schottky diode structure. There was a 7.5-nm-thick amorphous layer formed at the interface between Pt and InGaP after metal deposition. After annealing at 325 °C for 1 min, this amorphous layer increased to 12.8 nm and the reverse leakage current also decreased. The diffusion of Pt atoms and the crystallization of amorphous layer took place after annealing at 325 °C for 10 min. Prolonging the annealing to 3 h led to formation of Ga_2Pt and $GaPt_3$ phases in InGaP and Schottky diodes degraded after these new phases were observed. © *2008 American Institute of Physics*.
[DOI: 10.1063/1.2834849]

Aluminum-free InGaP semiconductor on GaAs has recently attracted a great deal of attention because of its microwave-device application possibilities.[1–5] InGaP has an edge over conventional AlGaAs for its wider band gap, high etching selectivity, low surface recombination velocity, less susceptibility to surface oxidation, and the absence of *DX* centers.[6] In the past few years, interfacial reactions of various Schottky-contact metals, such as Pt/Ti/Pt/Au,[5] Ti/Pt/Au,[7,8] WSiN,[9] and Cu/Au,[10–12] with the InGaP have been extensively studied, but none were proven perfect for technological implementations. The Schottky-contact qualities of InGaP/Ti/Pt/Au[7] and InGaP/WSiN,[8] for example, were found to degrade after a 500 °C heat treatment at which spurious CuP_2 for InGaP/Cu/Au has also been reported.[12]

In seeking solutions to surmount such interface-reaction problems, Pt has lately been used as a gate-sinking metal to keep the threshold voltage and leakage current under control for InGaP high electron mobility transistor devices[4] because of their higher Schottky barrier which could translate directly into reduced leakage current and thus also enhanced device performance.[5,13] Unfortunately, Nebauer *et al.*[3] has observed $GaPt_x$ compounds and other multicomponent phases while Ga_2Pt compound has also been detected using x-ray diffractometry[4] in the annealed Pt/InGaP junctions. Whether Pt can be an enabling Schottky metal or not would hence depend on how resilient it is to the thermal processing without interacting with the semiconductor. Nevertheless, the exact nature of this interface reaction remains unclear. This is possibly due to the difficulty in properly labeling Ga atoms in the InGaP/GaAs heterostructure and the lack of clear electron diffraction patterns necessary to help determine the zone axis of the InGaP semiconductor layer. There is thus an incentive to continue to better understand the Pt/InGaP interface properties to help shed some light on why Pt/Ti/Pt/Au metals fail as a good Schottky contact and whether a solution to can be found to prevent it.

In this work, the material stability and the interfacial reactions between Pt and InGaP were analyzed with high resolution transmission electron microscopy (HRTEM) while the current-voltage characteristics of Pt/InGaP Schottky diodes were also measured to seek correlations between the material structures and device performances. The heterostructure consists of, from bottom to top, a GaAs buffer layer, a 200 Å thick undoped $In_{0.49}Ga_{0.51}P$ Schottky layer, and a 750 Å thick heavily doped n^+-GaAs cap layer. The Schottky diode schematics were shown in Fig. 4 and fabricated by following steps: firstly, the Ohmic metal-contact metals Au/Ge/Ni/Au were deposited on the cap layer in sequence, and subsequently, the samples were annealed at 350 °C for 1 min to minimize the contact resistance. The

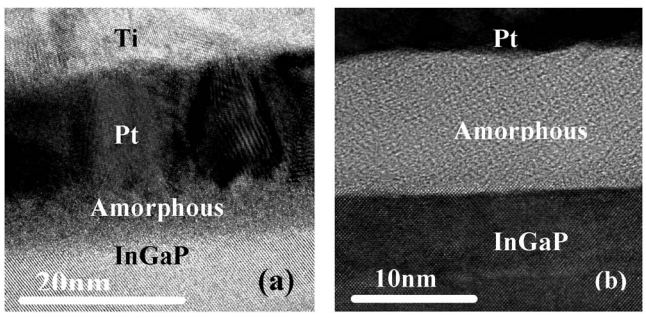

FIG. 1. (a) The cross-sectional HRTEM image of Pt and InGaP interface after metal deposition. (b) The cross-sectional HRTEM image of the Pt and InGaP interface after annealing at 325 °C for 1 min.

[a]NSC GSSAP Research Fellow, also with Texas Center for Superconductivity, University of Houston, Houston, Texas, USA.
[b]Electronic mail: edc@mail.nctu.edu.tw.
[c]Also with Dept of Physics and Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University, Taiwan.

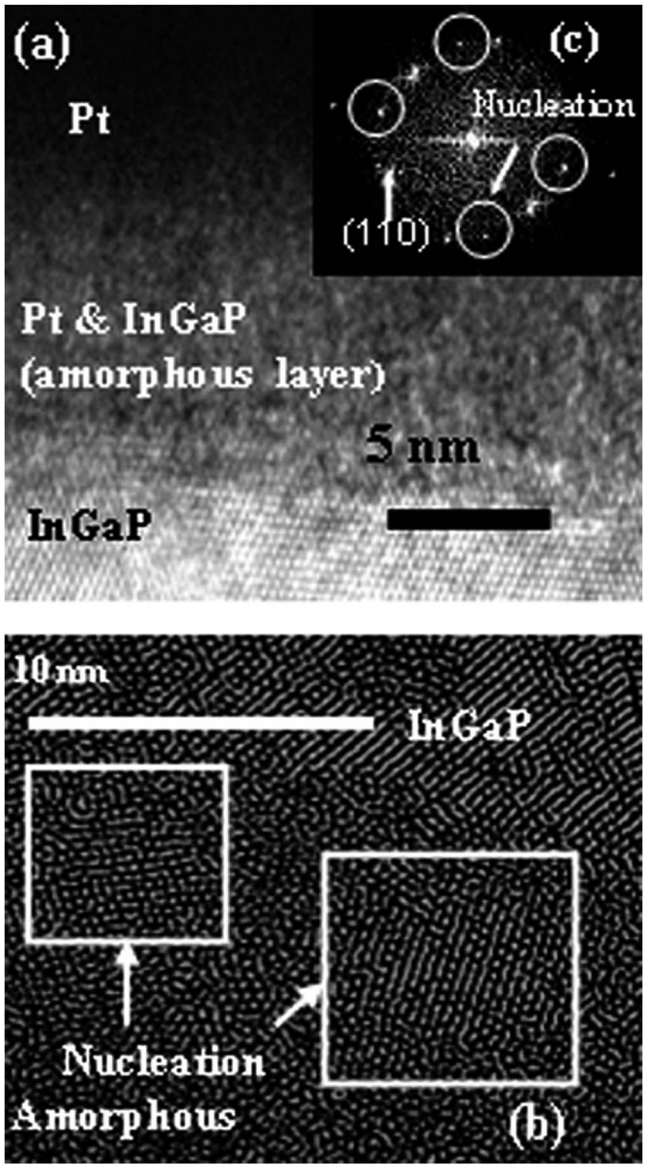

FIG. 2. (a) The cross-sectional HRTEM image of the Pt and InGaP interface after annealing at 325 °C for 10 min. (b) The fast Fourier transform (FFT) lattice image of the amorphous area which was shown in (a). The nucleation area was labeled by white square. (c) Nanobeam selected area electron diffraction pattern of the amorphous area shown in 2(a).

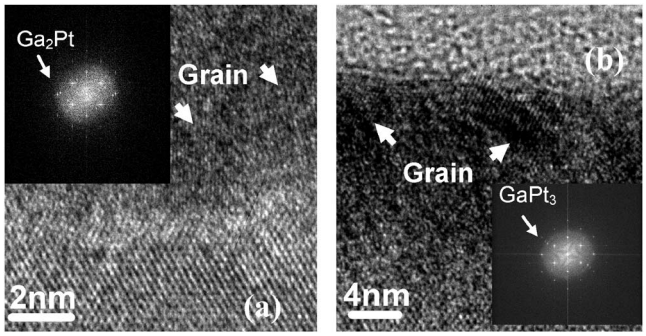

FIG. 3. (a) The cross-sectional HRTEM image of the Pt and InGaP interface after 325 °C annealing for 3 h and nanobeam selected area diffraction pattern showing the Ga_2Pt (422) phase. (b) The cross-sectional HRTEM image of Pt and InGaP interface after 325 °C annealing for 3 h and nanobeam selected area diffraction pattern showing the $GaPt_3$ (422) phase.

contact resistance (R_c) was measured via the transmission line model (TLM) method using 100 μm (W_x) × 75 μm (W_y) pads with interedge spacing of the neighboring pads (L) ranging from 36, 20, 10, 5, to 3 μm sequentially. The total resistance $R(L)=2R_c+R_s$, where R_s is the resistance of the sample of length L, width W_y and thickness t, and $R_S=\rho_s L/tW_y$. The sample sheet resistance $R_{\text{sheet}}=\rho_s/t$ hence $R(L)=2R_c+R_{\text{sheet}}L/W_y$. Hence, one can obtain $R(0)=2R_c$ by extrapolating the supposedly linear relation to $L=0$ to find the intercept of the R axis, while the slope represents R_{sheet}/W_y. Meanwhile, from the L-axis intercept $R(2L_t)=0$, one obtains $L_t=-R_cW_y/R_{\text{sheet}}$. Both R_c and the sample sheet resistance R_{sheet} of the semiconductor being measured follow naturally once the two intercepts are known. In the TLM method, all the voltage drops from the pads to the sample are assumed to be across the two neighboring edges of the pads on which the electrodes are placed (thus only W_y is relevant, but not W_x). With this in mind, we have $R_c=2.56\ \Omega$, $L_t=-1.06\ \mu$m, and $R_{\text{sheet}}=180\ \Omega/\square$ for the InGaP. These give the figure of merit $R_cW_y=0.19\ \Omega$ mm, as compared to the previously reported 0.14 Ω mm in Ref. 4 for a device structure of similar materials though somewhat differently configured, where the associated numbers are $W_y=75\ \mu$m, $R_c=1.93\ \Omega$, $L_t=-1.18\ \mu$m, and $R_{\text{sheet}}=123\ \Omega/\square$ for the InGaP.

The Schottky electrode consists of Au (300 nm)/Pt (100 nm)/Ti (100 nm)/Pt (20 nm) stack, placed directly on InGap after the n^+ GaAs layer was removed by a citric-acid/H_2O/H_2O_2 solution, all by e-beam evaporation. The 300 nm Au layer serves to lower the overall Schottky-metal resistance while the 100 nm Pt layer acts a diffusion barrier to prevent Au from diffusing into the Au/Pt/Ti/Pt/InGaP Schottky diode structure,[14] largely because of its high melting point and compatibility with the lift-off process. Note that in order to optimize the Schottky barrier height,[5] placed at the bottom of the metal stack is a 20 nm layer of Pt separated from the other 100 nm Pt layer by an also 100 nm thick Ti layer. Finally, these Schottky diodes were annealed, for various durations at 325 °C, which is 25 °C below Ohmic annealing temperature, avoiding affecting Ohmic contact resistance.

Energy dispersive x-ray (EDX) with electron beam of 2 nm spot size equipped on a HRTEM was performed for composition analysis. The HRTEM image showing the Pt/InGaP interface for an as-deposited sample is presented in Fig. 1(a). Each layer was identified by the nanobeam EDX analysis. As is obvious, there is a 7.5 nm thick amorphous layer existing at the Pt/InGaP interface and similar results were also found in the as-deposited Pt/GaAs interfaces[15] even for samples as-deposited at room temperature. The amorphous phase formation implicates the enormous inherent thermodynamic driving forces[15] that push the Pt atoms to migrate into the InGaP layer. After annealing at 325 °C for 1 min, the thickness of the amorphous layer increased from 7.5 to 12.8 nm. The diminution of the InGaP layer is due to the fact that more Pt atoms diffused into the pristine InGaP layer after thermal annealing. The diffusion boundary between InGaP and the amorphous layer was nonuniform, which could be caused by the nonuniform thermal process due to the short-time annealing.

Figure 2 (a) shows the HRTEM image of the Pt and InGaP interface reaction, whereas Fig. 2(c) gives the selected area diffraction patterns of the amorphous layer after 325 °C annealing for 10 min. Nucleation of crystalline phase occurred in the amorphous layer after annealing for 10 min at

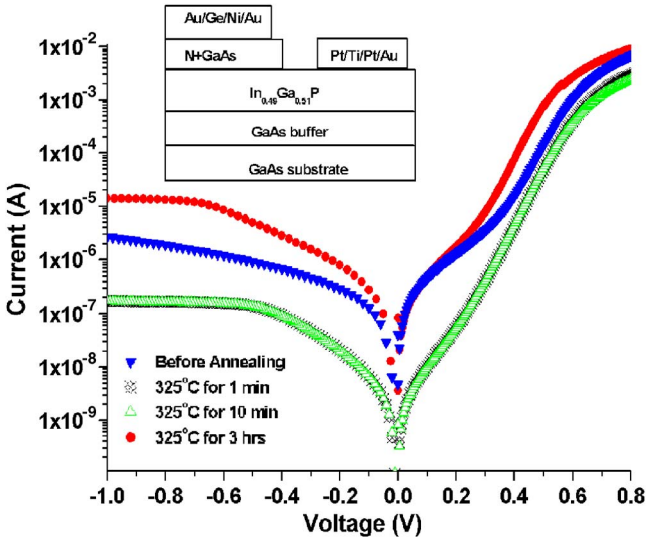

FIG. 4. (Color online) *I-V* characteristics of the Schottky diodes before and after annealing.

325 °C, as shown in Fig. 2(b). The HRTEM image of the InGaP/GaAs interface after annealing at 325 °C for 3 h is provided in Fig. 3(a). The crystalline grains were observed in the amorphous layer near its interface with InGaP and were identified as an orthorhombic Ga_2Pt (422) phase, judged from the nanobeam selected area diffraction patterns. The HRTEM image of the Pt/InGaP interface after annealing at 325 °C for 3 h is presented in Fig. 3(b). However, near the interface of the amorphous layer with Pt, a tetragonal $GaPt_3$ (422) phase was observed. On the basis of these observations, this thin amorphous layer, it can be concluded, could be a precursory step to forming more stable Ga_2Pt (422) and $GaPt_3$ (422) phases at the later stage of annealing. The new phases of the Ga_2Pt (422) and $GaPt_3$ (422) existed in different locations of the amorphous layer. The Ga_2Pt (422) near the InGaP layer was a result of the outdiffusion of Ga from InGaP into the amorphous layer, and $GaPt_3$ (422) was present near the alloy-Pt interface.

Figure 4 shows the *I-V* characteristics of the diodes before and after annealing, the leakage current decreased after 325 °C, 1 min annealing, possibly due to Pt diffusion.[16] After 325 °C annealing for 10 min, the diodes' performance remained almost unchanged even with the crystalline phase nucleated in the amorphous layer as shown in Fig. 2(b). In summary, the interfacial reactions between the Pt and the InGaP layer after thermal annealing has been investigated. A 7.5 nm-thick amorphous layer was formed between Pt and InGaP layer after the room-temperature gate-metal deposition. After annealing at 325°C for 10 minutes, crystallizations took place in the amorphous layer. At this stage, the thickness of amorphous layer remained unchanged; indicating that insertion of the Ti layer was effective as a diffusion barrier at 325°C. After annealing for 3 hours at 325 °C, however, stable phases of Ga_2Pt (422) and $GaPt_3$ (422) formed in the InGaP layer, though not in the Schottky metal stack, leading to degradation of the diode performances. However, the Ga_2Pt (422) phase was observed at the InGaP/GaAs interface, exhibiting continuing diffusion of Pt atoms beyond the 3-hour annealing. Thus, further study on the Pt diffusion at various annealing temperatures and durations for the contact metal stacks with, for example, thinner bottom Pt layers may be necessary to optimize the Schottky characteristics stabilization.

The authors would like to acknowledge the support from the National Science Council, and the Ministry of Economic Affairs, Taiwan, R.O.C., under the Contracts Nos. NSC 95-2752-E-009-001-PAE and 95-EC-17-A-05-S1-020. The work at Houston was supported in part by the U.S. National Science Foundation through Grant No. DMR-0404542, the U.S. Department of Energy through Grant No. DE-FG02-05ER46208, the U.S. Air Force Office of Scientific Research through Grant No. FA9550-06-1-0401, and the State of Texas Strategic Partnership for Research in Nanotechnology (SPRING) through the Texas Center for Superconductivity at the University of Houston.

[1]P. Fay, K. Stevens, J. Elliot, and N. Pan, IEEE Electron Device Lett. **20**, 554 (1999).
[2]Y. C. Lin, E. Y. Chang, H. M. Lee, and C. Y. Chang, Electron. Lett. **40**, 777 (2004).
[3]E. Nebauer, M. Mai, J. Wurfl, and W. Osterle, Semicond. Sci. Technol. **15**, 818 (2000).
[4]L. H. Chu, E. Y. Chang, L. Chang, Y. H. Wu, S. H. Chen, H. T. Hsu, T. L. Lee, Y. C. Lien, and C. Y. Chang, IEEE Electron Device Lett. **28**, 82 (2007).
[5]J. R. Lothian, F. Ren, J. M. Kuo, J. S. Weiner, and Y. K. Chen, Solid-State Electron. **41**, 673 (1997).
[6]M. O. Watanabe and Y. Ohba, J. Appl. Phys. **60**, 1032 (1986).
[7]C. T. Lee, H. P. Shiao, N. T. Yeh, C. D. Tsai, Y. T. Lyu, and Y. K. Tu, Solid-State Electron. **41**, 1 (1997).
[8]C. T. Lee, M. H. Lan, and C. D. Tasi, Solid-State Electron. **41**, 1715 (1997).
[9]K. Shiojima, K. Nishimura, and F. Hyuga, J. Vac. Sci. Technol. B **14**, 652 (1996).
[10]D. S. Liu, C. T. Lee, and C. W. Wang, J. Appl. Phys. **94**, 3805 (2003).
[11]D. S. Liu and C. T. Lee, J. Appl. Phys. **91**, 1349 (2002).
[12]D. S. Liu and C. T. Lee, J. Appl. Phys. **92**, 987 (2002).
[13]P. Fay, K. Stevens, J. Elliot, and N. Pan, IEEE Electron Device Lett. **20**, 554 (1999).
[14]G. Stareev, H. Kunzel, and G. Dortmann, J. Appl. Phys. **74**, 7344 (1993).
[15]C. Fontaine, T. Okumura, and K. N. Tu, J. Appl. Phys. **54**, 1404 (1983).
[16]S. Kim, I. Adesida, and H. Hwang, Appl. Phys. Lett. **87**, 232102 (2005).