ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT

Applied Surface Science 228 (2004) 5–9

applied surface science

www.elsevier.com/locate/apsusc

Short communication

Passivation of GaAs field-effect transistors in diluted S_2Cl_2 solution

Y. Wu[a], Y. Liu[a], X.M. Ding[a], E.G. Obbard[a], X.Z. Wang[a], H.J. Ding[a], X.Y. Hou[a,b,*], X.B. Li[c]

[a]*Applied Surface Physics Laboratory (National Key Laboratory), Fudan University, Shanghai 200433, PR China*
[b]*Institute of Advanced Materials and Technology, Fudan University, Shanghai 200433, PR China*
[c]*The Electronic 13th Research Institute, The Ministry of Information Industry, Sijiazhuang 050002, PR China*

Received 30 May 2003; received in revised form 30 May 2003; accepted 14 January 2004

Abstract

S_2Cl_2 diluted in the non-conductive CCl_4 solvent has been successfully applied to the passivation of GaAs field-effect transistors. In such a solution, in situ measurements of current–voltage (*I–V*) characteristics of the devices are accessible while the passivation is in process. By comparing the *I–V* data measured from the devices upon passivation in various concentrated S_2Cl_2 solutions, it is found that the volume ratio of 10^{-5} (S_2Cl_2:CCl_4) represents the optimal concentration where dipping of a device for 450 s or so will result in a 28% rise in breakdown voltage while the transconductance reduces only by 10%.
© 2004 Elsevier B.V. All rights reserved.

PACS: 81.65.Rv; 81.65.-b; 85.30.Tv; 81.05.Ea; 73.30.+y; 73.50.Gr; 73.61.Ey

Keywords: Passivation; Surface treatments; Field-effect devices; III–V semiconductors

1. Introduction

Sulfur passivation is an important technique to enhance the stability and performance of GaAs and other III–V compound devices. Ever since the work reported by Sandroff et al. [1], many new techniques have been invented [2–12] and applied to passivate the practical devices [13–20]. In these techniques, some liquid phase treatments are proved to be very effective. For example, $(NH_4)_2S$ [3], organic thiols [5], (CH_3CSNH_2) [9] and SeS_2:CS_2 [12] are used as the passivation solution. Among them, $(NH_4)_2S$ liquid phase treatment has been most widely applied to the passivation of practical devices. For instance, Dong et al. reported the technique using aqueous solution of $(NH_4)_2S$ to passivate metal-semiconductor field-effect transistors (MESFETs) [19]. In their work, after the MESFET was passivated by the $(NH_4)_2S$ solution at 60 °C for 10 min, the breakdown voltage could rise around 30% and the transconductance (G_M) decrease somewhat. Another inspiring work of Kang et al. [20] further developed the S-passivation technique on MESFET by adding hydrogenation to the process.

In previous work of Li et al. [6], a new sulfur passivation using oxygen-free S_2Cl_2 solution to replace the ordinary $(NH_4)_2S$ solution was developed and then successfully applied to passivate GaAs heterojunction bipolar transistors (HBTs) [13]. More

* Corresponding author. Fax: +86-6510-4949.
E-mail address: xyhou@fudan.edu.cn (X.Y. Hou).

0169-4332/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.apsusc.2004.01.037

recently, the study of Gnoth et al. [21] confirmed the S_2Cl_2 has a similar nature of S-III–V bonding to $(NH_4)_2S$ when used to passivate the GaAs surface. The extra advantage of S_2Cl_2 passivation is that its non-conductivity enables real-time monitoring of the treatment process. In this work, diluted S_2Cl_2 solution is used to passivate MESFETs, and two electric parameters, breakdown voltage and transconductance, are measured in real-time while both the passivation time and concentration of the solution are adjusted. The improvement of dc characteristic of MESFETs comparable with previous $(NH_4)_2S$ passivation work [19] is demonstrated. A detailed investigation on the use of real-time monitoring to optimize the passivation conditions is also presented. By passivating MESFET samples again under the same conditions and without real-time monitoring, we demonstrate the validity of our method to choose the optimal passivation conditions.

2. Experimental

The cross-section of the MESFET samples relevant is schematically shown in Fig 1a. The MESFET was grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. Ohmic contacts were made to the N^+ source and drain regions while the gate was formed via Schottky contact [19]. The remaining GaAs surfaces between source and the gate and between drain and the gate, the positions where S_2Cl_2 and GaAs react, were uncoated. The gate length

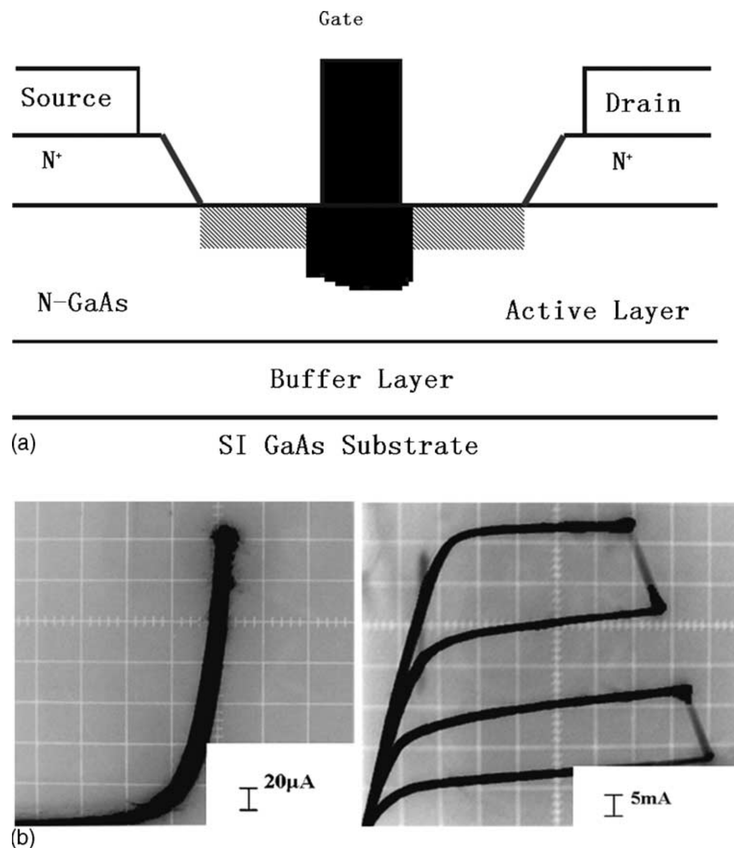

Fig. 1. (a) Schematic cross-section of the MESFET samples studied. (b) Real-time picture taken from the oscilloscope. The left, the dependence of the current flowing between the drain and gate on the voltage applied (where $I_{dg} = 20$ μA/div, $V_{dg} = 5$ V/div); the right, common emitter characteristic (where $I_{ds} = 5$ mA/div, $V_{ds} = 1$ V/div and V_{gs} corresponding to the four contours are 0, −0.5, −1.0 and −1.5 V, respectively).

and width were 0.8 and 125 μm, respectively. The gate-source and gate-drain separations were both 2.5 μm. The electric parameters are measured on the platform by pinning the testing probes on the contact pads of the MESFET samples.

Our experiment is carried out as follows: having been ultrasonically cleaned using acetone, ethanol and deionized water in sequence and then blown dry by nitrogen gas, the samples were placed into a glass vessel containing diluted S_2Cl_2 solution. The glass vessel was then put together with the sample on a platform in order to measure its electric parameters before and during the passivation. Two representative dc parameters were measured: the break-down voltage, V_{BR}, defined as the voltage across the drain and gate when the current reaches 0.1 mA, in the condition of source open; transconductance, G_M, defined as the variation of the current between the drain and source (I_{ds}) divided by the voltage across the gate and the source (V_{gs}), in the condition of the voltage between the drain and the source (V_{ds}) fixed, say, at 5 V. Fig. 1b shows the real-time picture taken from the oscilloscope. The left figure, from which V_{BR} can be determined, shows the dependence of current flowing

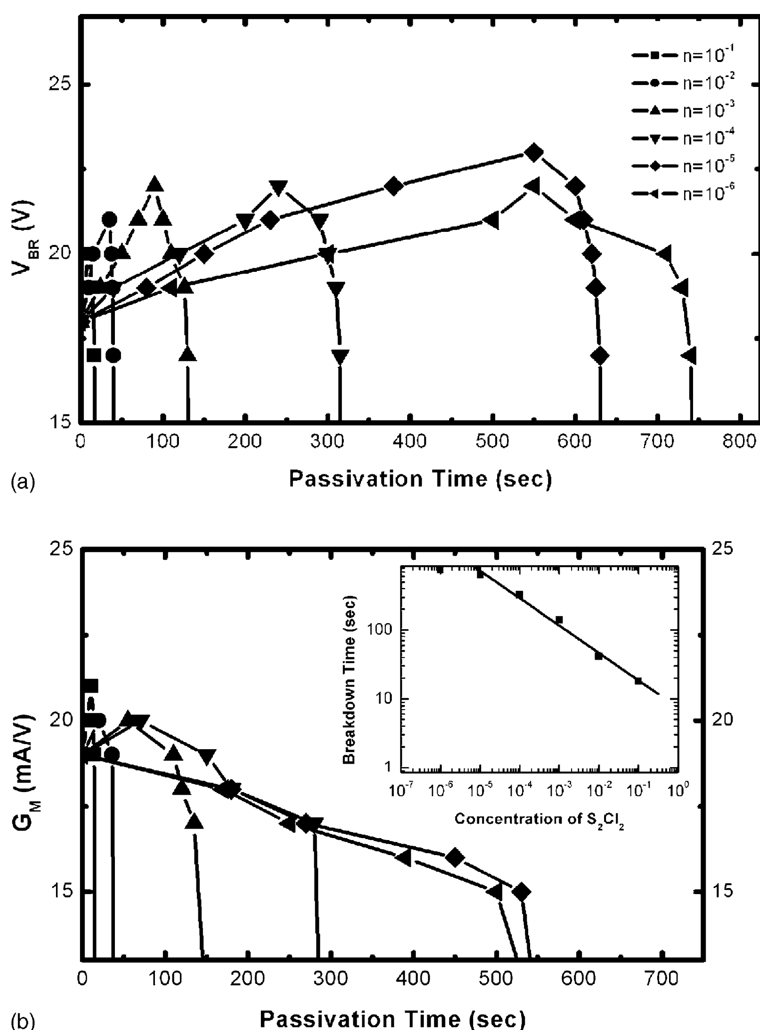

Fig. 2. Real-time data of V_{BR} (a) and G_M (b) at different passivation time and in different concentration of S_2Cl_2 solution. The inset shows the dependence of breakdown time on concentration of S_2Cl_2 (n) in log scales.

between the drain and gate on the voltage applied; the right figure, from which G_M can be determined, shows the common emitter characteristic. The procedure is repeated for various concentrations, n, of S_2Cl_2 solutions: 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6}. Here concentration (n) is defined as the volume ratio of S_2Cl_2:CCl_4.

3. Results and discussion

Fig. 2a shows the dependence of V_{BR} on the passivation time under conditions of various concentrations of S_2Cl_2 solution. Before passivation, average V_{BR} is 18 V. After the passivation started, V_{BR} increases and reaches a maximum before the MESFET sample breaks down. The higher the concentration, the quicker the V_{BR} reaches a maximum. When $n = 10^{-5}$ and under 9 min passivating, the breakdown characteristic is greatly improved and a 5 V enhancement of V_{BR} from 18 to 23 V is achieved. It is evident that the S_2Cl_2 treatment effectively modifies the device surface. As generally recognized, high surface recombination rates and bound surface charges can be mainly attributed to the native oxides and to various recombination centers. The reaction between S_2Cl_2 and GaAs can quickly form a sulfur-terminated layer [21]. The formation of Ga–S and As–S on the GaAs surface greatly reduces both the recombination rate and the number of bound surface charges [22], and thereby contributes to the increase of the V_{BR} [19]. As passivation continues, the S-containing S_2Cl_2 solution will, in addition to passivating the surface, etch away GaAs until the MESFET sample breaks down [13]. In order to obtain good breakdown features, removal of native oxides and prevention of the surface from further etching are equally crucial. The optimal passivation time should be properly chosen so as to replace the oxide layer with sulfur-terminated layer while not overetching the GaAs surface.

Fig. 2b shows the dependence of G_M on the passivation time under conditions of different concentrations. Before passivation, average G_M is 19 mA/V. Under conditions with S_2Cl_2 concentration higher than 10^{-4}, G_M reaches a maximum and then decreases before the MESFET sample breaks down. When the concentration is less than 10^{-4}, G_M simply drops without ever reaching a maximum. According to the data, G_M ranges from 15 to 21 mA/V, so that G_M may be adjusted within this range when selecting proper passivation conditions. G_M can be adjusted to meet different practical requirements: a decrease of G_M indicates a wider base voltage range; an increase of G_M is essential to achieve higher power [19].

The inset in Fig. 2b shows the dependence of breakdown time (defined as the time when the MESFET sample breaks down) on the concentration of S_2Cl_2 solution (n) in log scales. All the data points lie on a line except the (10^{-6}) point. This line is important because it separates all passivation conditions into two regions: above the line is the breakdown region, and viable passivation conditions should be chosen from the region below the line.

The comparison between the passivation results with and without monitoring is shown in Fig. 3. The concentration of S_2Cl_2 solution is 10^{-5} in both cases. The general trend of V_{BR} is naturally uninfluenced by real-time monitoring. Although exact breakdown times of the monitored samples and unmonitored samples do not coincide, the passivation results are not significantly affected by the real-time monitoring, and our optimal conditions obtained through such monitoring are considered valid and reliable.

Besides the electrical parameters, process stability is an important factor in choosing the optimal conditions for practical passivation. For instance, a G_M of

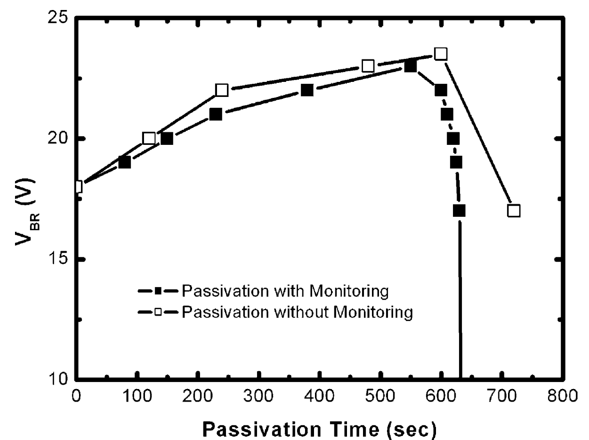

Fig. 3. Comparison between passivations with and without monitoring. The open symbols indicate the data of V_{BR} without monitoring; the dark ones correspond to data obtained through real-time monitoring. Both are carried out in the 10^{-5} diluted S_2Cl_2 solution.

21 mA/V can be reached by dipping the sample into 10^{-1} S_2Cl_2 solution for 11 s. However, the sample will break down if dipped two more seconds. This condition is obviously undesirable for stable and controllable passivation. With all factors comprehensively considered, the condition of the 10^{-5} S_2Cl_2 and 450 s is most stable and favorable, under which about 28% increase of V_{BR} and 10% decrease of G_M are achieved. If the decrease of G_M is unacceptable, passivating for 150 s in 10^{-4} S_2Cl_2 gives about 12% increase of V_{BR} and none decrease of G_M [23].

4. Conclusion

Real-time monitoring is a very effective and viable technical method to optimize the condition of S_2Cl_2 passivation of GaAs MESFETs. This method may be applied to all liquid phase treatments, provided the passivation solution is non-conductive. By adjusting two parameters (the passivation time and the concentration of the S_2Cl_2 solution), optimal conditions can be easily determined according to different requirements. In this work, significant improvement of the dc characteristics of MESFETs has been achieved and two sets of optimal conditions for different requirements are given. We also proved the validity of real-time monitoring by ruling out any significant distortion of passivation results by the monitoring system.

References

[1] C.J. Sandroff, R.N. Nottenburg, J.C. Bischoff, R. Bhat, Appl. Phys. Lett. 51 (1987) 33.

[2] M.S. Carpenter, M.R. Melloch, T.E. Dungan, Appl. Phys. Lett. 53 (1988) 66.

[3] C.J. Spindt, D. Liu, K. Miyano, P.L. Meissner, T.T. Chiang, T. Kendelewicz, I. Lindau, W.E. Spicer, Appl. Phys. Lett. 55 (1989) 861.

[4] E. Yablonovitch, T.J. Gmitter, B.G. Bagley, Appl. Phys. Lett. 57 (1990) 2241.

[5] S.R. Lunt, P.G. Santangelo, N.S. Lewis, J. Vac. Sci. Technol. B 9 (1991) 2333.

[6] Z.S. Li, W.Z. Cai, R.Z. Su, G.S. Dong, D.M. Huang, X.M. Ding, X.Y. Hou, X. Wang, Appl. Phys. Lett. 64 (1994) 3425.

[7] A.N. MacInnes, M.B. Power, A.R. Barron, P.P. Jenkins, A.F. Hepp, Appl. Phys. Lett. 62 (1993) 711.

[8] X.Y. Hou, X.Y. Chen, Z.S. Li, X.M. Ding, X. Wang, Appl. Phys. Lett. 69 (1996) 1429.

[9] E.D. Lu, F.P. Zhang, S.H. Xu, X.J. Yu, P.S. Xu, Z.F. Han, F.Q. Xu, X.Y. Zhang, Appl. Phys. Lett. 69 (1996) 2282.

[10] X.A. Cao, H.T. Hu, X.M. Ding, Z.L. Yuan, Y. Dong, X.Y. Chen, B. Lai, X.Y. Hou, J. Vac. Sci. Technol. B 16 (1998) 2656.

[11] H. Shen, W. Zhou, J. Pamulapati, Appl. Phys. Lett. 74 (1999) 1430.

[12] J. Sun, D.J. Seo, W.L. Obrien, F.J. Himpsel, A.B. Ellis, T.F. Kuech, J. Appl. Phys., 85 (1999) 969.

[13] X.A. Cao, X.Y. Hou, X.Y. Chen, Z.S. Li, R.Z. Su, X.M. Ding, X. Wang, Appl. Phys. Lett. 70 (1997) 747.

[14] R.S. Beister, J. Maege, D. Gutsche, G. Erbert, J. Sebastian, K. Vogel, M. Weyers, J. Wurfl, O.P. Daga, Appl. Phys. Lett. 68 (1996) 2467.

[15] S. Kamiyama, Y. Mori, Y. Takahashi, K. Ohnaka, Appl. Phys. Lett. 58 (1991) 2595.

[16] U. Schede, St. Kollakowski, E.H. Bottcher, D. Bimberg, Appl. Phys. Lett. 64 (1994) 1389.

[17] Y.-H. Jeong, K.-H. Choi, S.-K. Jo, B. Kang, Jpn. J. Appl. Phys. Part 1 34 (1995) 1176.

[18] P.P. Jenkins, A.N. MacInnes, M. Tabib-Azar, A.R. Barron, Science 263 (1994) 1751.

[19] Y. Dong, X.M. Ding, X.Y. Hou, Appl. Phys. Lett. 77 (2000) 3839.

[20] M.G. Kang, H.H. Parka, H. Kim, Appl. Phys. Lett. 80 (2002) 2499.

[21] D.N. Gnoth, D. Wolfframm, A. Patchett, S. Hohenecker, D.R.T. Zahn, A. Leslie, I.T. McGovern, D.A. Evans, Appl. Surf. Sci. 123 (1998) 120.

[22] N. Yashida, M. Totsuka, J. Ino, S. Matsumoto, Jpn. J. Appl. Phys. Part 1 33 (1994) 1248.

[23] In order to give more accurate passivation data, these results are obtained under the conditions without real-time monitoring. So they are not exactly the same as the data shown in Fig. 2.