HBTs with a planar-type extended base as a hydrogen-sensitive sensor

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Abstract

A hydrogen sensing transistor fabricated by a heterojunction bipolar transistor (HBT) with an extended base (EB) formed by a metal-semiconductor-metal (MSM) hydrogen sensor is reported. The power consumption in stand-by mode is smaller than 2 μW. Common-emitter characteristics show that the sensing base (collector) current gains at 25 in 0.01%, 0.1%, and 1% H2/N2 are as high as 75 (512), 134, (977), and 233 (2.89 ? 104), respectively. Low-power consumption and high-sensitive gains are indicative that our HBT together with planar-type MSM sensor is very promising for applications to hydrogen sensing transistors using one voltage source.

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A hydrogen sensing transistor fabricated by a heterojunction bipolar transistor (HBT) with an extended base (EB) formed by a metal-semiconductor-metal (MSM) hydrogen sensor is reported. The power consumption in stand-by mode is smaller than 2 μW. Common-emitter characteristics show that the sensing base (collector) current gains at 25 in 0.01%, 0.1%, and 1% H_2/N_2 are as high as 75 (512), 134, (977), and 233 (2.89×10^4), respectively. Low-power consumption and high-sensitive gains are indicative that our HBT together with planar-type MSM sensor is very promising for applications to hydrogen sensing transistors using one voltage source.

Introduction: To develop high-sensitive sensors is demanded since hydrogen is widely applied as energy carrier. Benefit from first report on detecting hydrogen with a Si-based metal oxide semiconductor (MOS) structure [1], a lot of studies on various structures were then provided. In particular, a metal-semiconductor (MS) diode [2-4] and a field-effect transistor (FET) [5-7] are two widely accepted hydrogen sensors. Ohmic and Schottky contacts cannot be formed by using different high-cost metals on the same layer in fabricating the MS diode. Besides, a MS diode as a hydrogen sensor is generally forward biased [3, 4]. Undesirable power consumption has to be concerned in stand-by situation. Three-terminal FETs having catalytic metal (Pd or Pt) be their gate metal. However, both a positive and a negative source are needed for a depletion-mode FET [6, 7]. Power consumption in stand-by situation is still an issue. Fortunately, a metal-semiconductor-metal (MSM) diode was reported to have two Schottky contacts on the same layer [8, 9]. Furthermore, only one source is required to obtain current-voltage characteristics and a very small stand-by current is expected. In this letter, a bipolar-type HBT structure used to fabricate a hydrogen sensing transistor is proposed. A planar-type MSM diode forming on the low-doping collector layer was employed as the extended-base hydrogen sensor. Compared to FETs, bipolar-type transistors also require only one positive source. Thus, low-power consumption and high-sensitive gains were achieved for the hydrogen sensing transistor.

Device fabrication and measurement: Fig. 1 shows a schematic diagram of a proposed hydrogen sensing transistor. An InGaP-GaAs HBT is used as a current amplify transistor while a MSM diode is employed as a hydrogen-sensitive sensor. The HBT structure deposited on a (100)-oriented semi-insulating GaAs substrate was employed. It was prepared by a metal-organic chemical vapour deposition (MOCVD) system and consisted of a 0.6 μm n^+ -GaAs ($n^+ = 5\times10^{18}$cm^{-3}) sub-collector layer, a 0.8 μm low-dopingn^- -GaAs ($n^- = 8\times10^{16}$ cm^{-3}) collector layer, a 0.08 μm highly-doping p^+ -GaAs ($p^+ = 4\times10^{19}$cm^{-3}) base layer, a 0.03 μm n -InGaP ($n = 3\times10^{17}$ cm^{-3}) emitter layer, and a 0.2 μm n^+ -GaAs ($n^+ = 3\times10^{18}$ cm^{-3}) sub-emitter layer together with a 0.1 μmn^+ -$In_xGa_{1-x}As$ ($x = 0$ to 0.7 in 0.05 μm and $x = 0.7$ in 0.05 μm) cap layer. Manufacturing processes of the HBT started with the emitter and the base mesas. Ohmic contacts for the emitter (E), the collector (C), and the base (B') were formed by depositing AuGeNi and AuZn upon the cap, the sub-collector, and the base layers, respectively. After removing the cap, the emitter, and the base layers in the hydrogen-sensor region, two coplanar multiple-finger electrodes were formed by depositing a 30 nm mixture of Pd and SiO_2[8]. The extended base (EB) using the MSM diode was hence achieved.

To measure sensing properties of as-fabricated hydrogen sensing transistor, 50 ppm to 1% H_2/N_2 gases were employed by using a custom-made, flow-through 4-pin testing chamber. Sensing properties of the EB-hydrogen sensor were obtained by applying a voltage of $V_{BB'}$ and introducing air/N_2 and various H_2/N_2gases into the chamber. Sensing diode currents obtained in N_2 and H_2/N_2 are denoted as I_{DH} and I_{DN} , respectively. Electrical properties of the HBT were measured by using the electrodes E, B', and C. In contrast, sensing properties of the hydrogen sensing transistor were measured by using the electrodes E, B, and C. At the present measurement, sensing base and collector currents (I_{BN} , I_{BH} andI_{CN} , I_{CH}) reflecting N_2 and H_2/N_2 were employed as output signals. Furthermore, a sensing base (collector) current gain of $G_B = I_{BH} / I_{BN}$($G_C = I_{CH} / I_{CN}$) was defined to evaluate our hydrogen sensing transistor.

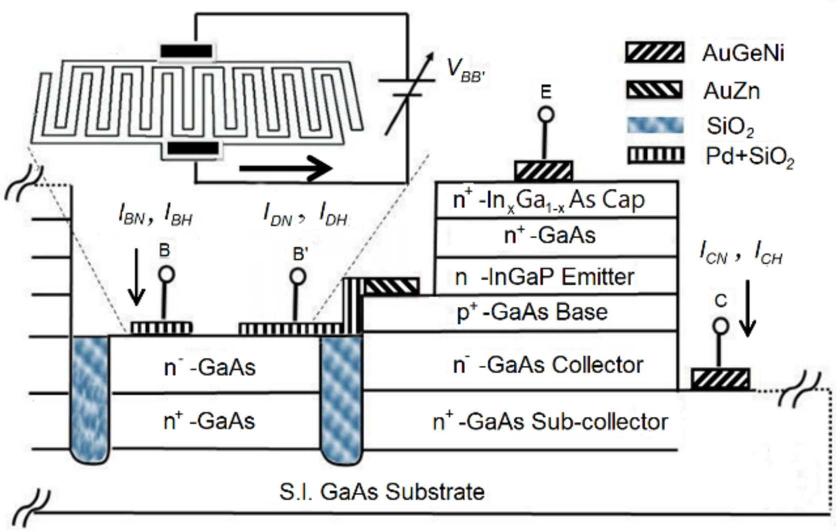

Fig. 1 *Schematic diagram of the HBT fabricated with a planar-type extended base as hydrogen sensitive sensor.*

Results and Discussion: Fig. 2 shows common-emitter sensing characteristics of the hydrogen sensing transistor at various temperatures. The biased voltage is $V_{BE} = 3$ V. Obviously, sensing currents flowing through the base-emitter junction (i.e., $I_{DN} = I_{BN}$ and$I_{DH} = I_{BH}$ in Fig. 1) will be dominated by the MSM diode. They will then be amplified as the collector currents (I_{CN} andI_{CH}). We firstly find thatI_{CN} for the hydrogen sensing transistor in N_2 are as small as 0.0125, 0.095, 0.14, and 0.23 μA at 25, 50, 80, and

110, respectively. In facts, measured $I_{CN}s$ are very close to $I_{BN}s$. This is because $I_{BN}s$ are so small that no gain is available for the HBT. Thus, stand-by power consumption smaller than 2 µw is expected at V_{CE}= 5 V. Considering effects of ambient temperatures on the sensing properties, I_{CH} increases from 13.5 µA at 25 to 60.1 µA at 50, then to 163 µA at 80, and finally to 220 µA at 110, at V_{CE} = 3 V in a 0.01% H_2/N_2. Improved $I_{CH}s$ are due mainly to the fact that the thermal emission current of the MS diode increases with increasing temperature. On the other hand, experiments also reveal that I_{CH} at V_{CE} = 3 V at 50 increases from 60.1 µA to 137 µA and then to 181 µA when the hydrogen concentration increases from 0.01% to 0.1% and then to 1%, respectively. Since more dipoles will be formed at MS interface in higher H_2/N_2, a larger Schottky barrier-height variation ($\Delta\varphi_{B\nu}$) is achieved to bring about a higher I_{DH} and hence a higher I_{CH} [4].

Fig. 3a shows dynamic-state sensing currents of the MSM diode biased at $V_{BB'}$ = 1 V at 25 (solid line) and 50 (dashed line). A sensing diode current starts to increase from the I_{DN} = 1.57×10^{-3} µA at the moment the 1% H_2/N_2 is introduced at 25. After the sensing diode current saturates at $I_{DH,sat}$ = 0.35 µA, air and then pure nitrogen gas are used to remove the 1% H_2/N_2. The sensing diode current will then return to the I_{DN} . Measurements have been repeatedly performed by introducing 0.1% H_2/N_2, air/N_2, 0.01% H_2/N_2, and air/N_2 to the MSM hydrogen sensor at 25. Measured $I_{DH,sat}s$ are 0.23 and 0.14 µA in 0.1% and 0.01% H_2/N_2, respectively. Similar experiments have also been performed at 50. G_Ds were thus calculated to be 87 (314), 146

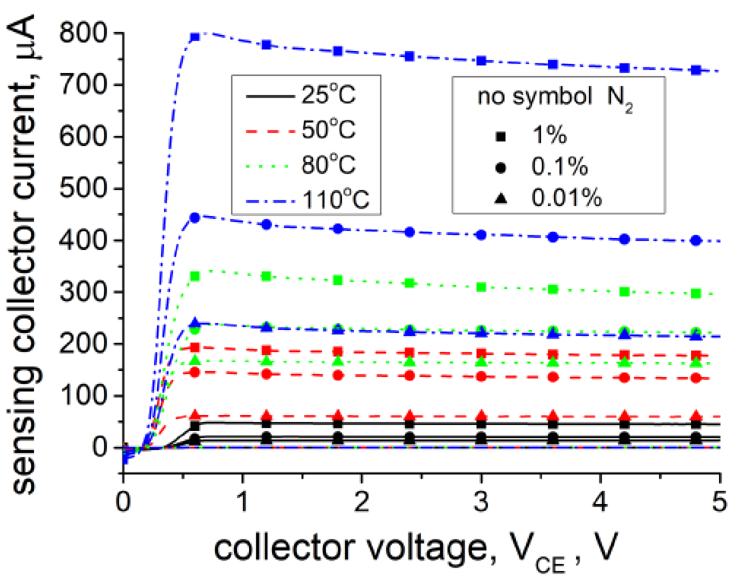

Fig. 2 *Common-emitter sensing properties of the hydrogen sensing transistor at various temperatures in 0.01%, 0.1%, and 1% H_2/N_2.*

(898), and 223 (974) at 25 (50) in 0.01%, 0.1%, and 1% H_2N_2, respectively. Sensing base and collector currents measured for the hydrogen sensing transistor are shown in Figs. 3b and 3c. It is found that (i) I_{BN} = 1.88×10^{-3} µA and (ii) I_{BH} is very close I_{DH} . The $I_{DH,sat}$ saturates at 0.35 µA (2.3 µA) while $I_{BH,sat}$ does at 0.44 µA (2.7 µA) in 1% H_2/N_2 at 25 (50). Such a bit of difference is due to the slightly different voltage across the MSM diode between the EB hydrogen sensor and the hydrogen sensing transistor. However, $I_{CH,sat}$ is much larger than $I_{DH,sat}$ and $I_{BH,sat}$. This is reasonable since $I_{BH,sat}$ is amplified by the current amplify transistor. Calculated G_{BS} , G_{CS} at 25 (50) in 0.01%, 0.1%, and 1% are 75, 512 (379, 1.66×10^4), 134, 977 (1.04×10^3, 2.78×10^4), and 233, 2.89×10^4 (941, 3.41×10^4), respectively. Experimental results also prove that our HBT and MSM are successfully used as a current amplifier and EB-hydrogen sensor.

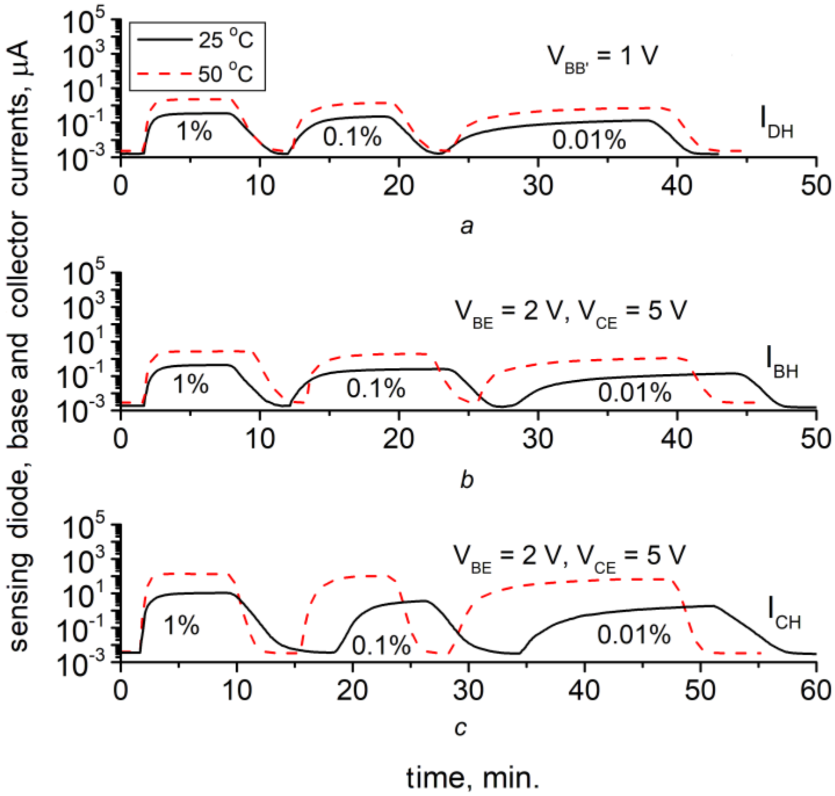

Fig. 3 *Dynamic-state sensing properties at 25 (solid line) and 50 (dashed line) in 0.01%, 0.1%, and 1% H_2/N_2.*

a $I_{DH,}$ MSM diode biased at $V_{BB'} = 1$ V.

b $I_{BH,}$ hydrogen sensing transistor biased at $V_{BE} = 2$ V and $V_{CE} = 5$ V.

c I_{CH} , hydrogen sensing transistor biased at $V_{BE} = 2$ V and $V_{CE} = 5$ V.

Another key merit used to evaluate a gas sensor is response time (t_a) defined as the time required for the sensing current to reach (1-e^{-1}) of total change [9]. Table 1 summarize current gains and response times obtained from measured sensing diode, base, and collector currents. A higher hydrogen concentration or a higher temperature produces a shorter response time.$t_{a,D}$ and $t_{a,B}$ obtained from I_{DH} and I_{BH} at 25 in 0.01% H_2/N_2 are 485 and 490 s while$t_{a,C}$ obtained from I_{CH} is 745 s. At 50, $t_{a,C}$ is still larger than$t_{a,D}$ and $t_{a,B}$. When 0.1% and 1% H_2/N_2 were introduced, relationship among $t_{a,D}$,$t_{a,B}$, and $t_{a,C}$ at both 25and 50 was not changed. That is, $t_{a,B}$ is nearly equal to $t_{a,D}$, which is shorter than$t_{a,C}$. The extended base determines bothI_{DH} and I_{BH} . As a result, the response times from I_{DH} andI_{BH} reasonably equal each other. A new finding is that the response time from I_{CH} is different from that from I_{BH} . Accordingly, the sensing base current at I_{BN} has to reach (1-e^{-1}) × $I_{BH,sat}$ to finish its response while it is from I_{CN} to (1-e^{-1})x$I_{CH,sat}$ for the sensing collector current. Owing to the current gain (β) at (1-e^{-1}) × $I_{BH,sat}$ is smaller than that at $I_{CH,sat}$. We thus concluded that (i) it will take more time for I_{CH} to satisfy the quantitative definition on response time and (ii) the HBT integrated to the MSM EB sensor does not produce time delay in sensing.

Conclusion: We have proposed a new hydrogen sensing transistor with low-power consumption in stand-by mode and high-sensitive gains in common-emitter mode. The hydrogen sensing transistor is fabricated by using an HBT with a MSM Schottky diode as an extended-base hydrogen sensor. Measured $I_{CN}s$ for the hydrogen sensing transistor in N_2 are as small as 0.0125, 0.095, 0.14, and 0.23 μA at 25, 50, 80, and 110 while I_{CH}s at $V_{CE} = 3$ V in 0.01% H_2/N_2 are increased from 13.5 μA at 25 to 60.1 μA at 50, then to 163 μA at 80, and finally to 220 μA at 110. In addition, experiments reveal that the power consumption in stand-by mode is smaller than 2 μW and the sensing collector current gains at 25 in 0.01%, 0.1%, and 1% H_2/N_2 are as high as 512, 977, and 2.89×10^4, respectively.

Table 1: Sensing diode, base, and collector current gains and corresponding response times for our hydrogen sensing transistor.

H_2/N_2 (%)	Temp. ()	G_D	G_B	G_C	$t_{a,D}$ (s)	$t_{a,B}$ (s)	$t_{a,C}$ (s)
0.01	25	81	75	512	485	490	745
	50	314	379	16610	350	355	390
0.1	25	145	134	977	165	170	240
	50	898	1042	27800	140	145	180
1	25	221	233	2890	60	65	85
	50	974	941	34100	50	55	70

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References

1. Lundstrom, I., Shivaraman, S., Svensson, A.: 'A hydrogen sensitive Pd-gate MOS transistor', *J. Appl. Phys.* , 1975, **46** , (9), pp. 3876–3881, doi: 10.1063/1.322185
2. Chen, H.I., Cheng, Y.C., Chang, C.H., Chen, W.C., Liu, I.P., Lin, K.W., Liu, W.C.: 'Hydrogen-sensing performance of a Pd nanoparticle/Pd film/GaN-based diode', *Sens. Actuators B,* 2017 **247** , pp. 514-519, doi: org/10.1016/j.snb.2017.03.039
3. Huang, J.R., Hsu, W.C., Chen H.I., Liu W.C.: 'Comparative study of hydrogen sensing characteristics of a Pd/GaN Schottky diode in air and N_2 atmospheres', *Sens. Actuators B* , 2007,**123** , (2), pp. 1040–1048, doi: 10.1016/j.snb.2006.11.008
4. Song, J., Lu, W.: 'Thermodynamic and kinetic analysis of hydrogen sensing in Pt/AlGaN/GaN Schottky diodes at high temperatures',*IEEE Sens. J.* , 2008, **8** , (6), pp. 903–909, doi: 10.1109/JSEN.2008.923938
5. Consejo, C., Prystawko, P., Knap, W., Nowakowska-Siwinska, A., Perlin, P., Leszczynski, M.: 'Mechanism of hydrogen sensing by AlGaN/GaN Pt-gate field effect transistors: magnetoresistance studies',*IEEE Sens. J.* , 2015, **15** , (1), pp. 123–127, doi: 10.1109/JSEN.2014.2340436
6. Hung, C.W., Lin, H.L., Chen, H.I., Tsai, Y.Y., Lai, P.H., Fu, S.I., Chuang, H.M., Liu, W.C.: 'Comprehensive study of a Pd-GaAs high electron mobility transistor (HEMT)-based hydrogen sensor',*Sens. Actuators B* , 2007, **122** , pp. 81-88, doi: 10.1016/j.snb.2006.05.007
7. Scharnagl, K., Eriksson, M., Karthigeyan, A., Burgmair, M., Zimmer, M., Eisele, I.: 'Hydrogen detection at high concentrations with stabilized palladium', *Sens. Actuators B* , 2001, **78** , pp. 138–143, doi: 10.1016/S0925-4005(01)00804-8
8. Chiu, S.Y., Huang, H.W., Huang, T.H., Liang, K.C., Liu, K.P., Tsai, J.H., Lour, W.S.: 'High-sensitivity metal-semiconductor-metal hydrogen sensors with a mixture of Pd and SiO_2 forming three-dimensional dipoles', *IEEE Electron Device Lett.* , 2008,**29** , (12), pp. 1328–1331, doi: 10.1109/led.2008.2006994

9. Chiu, S.Y., Huang, H.W., Liang, K.C., Huang, T.H., Liu, K.P., Tsai, J.H., Lour, W.S.: 'GaN hydrogen sensor with Pd-SiO_2mixture forming sensing nanoparticles', *Electron. Lett.* , 2009,**45** , (4), pp. 231–233, doi: 10.1049/el:20092158