Temperature Compensated Hall-Effect Power IC for Brushless Motor

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Abstract: In this paper we present a novel temperature compensated Hall effect power IC for accurate operation of wide temperature and high current drive of the motor coil. In order to compensate the temperature dependence of Hall sensitivity with negative temperature coefficient(TC), the differential amplifier has the gain consisted of epi-layer resistor with positive TC. The material of Hall device and epi-resistor is epi-layer with the same mobility. The variation of Hall sensitivity is -38% at 150°C and 88% at -40°C. But the operating point(B_{OP}) and release point(B_{RP}) of the Hall power IC are within ±25%. The experimental results show very stable and accurate performance over wide temperature range of -40°C to 125°C.

1. Introduction

Integrated circuits with Hall-effect devices(Hall IC's) have great potential application in various fields due to their ability to sense magnetic signals and process the signals on a chip.[1]

The application of Hall IC's containing power transistor will be wide spread. For example, Hall power IC's can drive a brushless motor directly. Since Hall brushless motors guarantee noiseless, highly reliable, and accurate operation. They are very attractive for use in video-tape recorders, video-disc players, and cooling fans.[2]

The important parameters of Hall IC's are the offset voltage and the sensitivity. The sensitivity of the Hall device is the change in output voltage per unit change in applied magnetic fields.

The sensitivity of Hall IC's is subject to changes with the temperature. The materials suitable for Hall IC's generally exhibit large increases in resistance with increasing temperature. Thus, a fixed voltage applied to the Hall device results in a current therethrough which decreases rapidly with increasing temperature. As a result of the decreasing current the sensitivity of the Hall device decrease. Therefore the thermal defects of Hall power IC must be compensated for accurate operation of wide temperature range and high current drive of the motor coil.

In this paper, the temperature compensation of Hall power IC's for brushless motor is presented. By experimental results we have verified the thermal characteristics of Hall power IC's and the performance of the brushless motor

2. Temperature dependence of the Hall device and epi-resistor

The Hall voltage of the Hall device is given as [3]

$$V_H = \frac{R_H GIB}{t} = \frac{G r_n IB}{qnt} \tag{1}$$

here R_H denotes the Hall coefficient, G the geometric correction factor, B the magnetic field, r_n the scattering factor, q the electron charge, n the carrier density, I the bias current of the Hall device, t the thickness of the Hall device. The supply-voltage related sensitivity is normally defined as [3]

$$S_V = \frac{V_H}{BV_S} \tag{2}$$

where V_S is supply voltage of Hall device. In case of an extrinsic n-type semiconductor[3]

$$S_V = r_n \mu_n \left(\frac{GW}{L}\right) \tag{3}$$

where W the width, L the length of the Hall device, μ_n the drift mobility. Differentiating Eq.(3) with respect to temperature and yields

$$\frac{\partial S_V}{\partial T} = \alpha \times \frac{\partial \mu_n}{\partial T} \tag{4}$$

where $\alpha = \frac{GW}{r_n L}$

$$\frac{\partial S_V}{\partial T} \propto \frac{\partial \mu_n}{\partial T} \tag{5}$$

The resistance of epi-layer is defined as [4]

$$R_{EPI} = \frac{L_{EPI}}{W_{EPI}} \times \frac{1}{q\mu_n N_D t_{EPI}} \tag{6}$$

where L_{EPI} the length, W_{EPI} the width, t_{EPI} the thickness of the Epi-resistor, N_D the n-type doping concentration. Differentiating Eq.(6) with respect to temperature and yields

$$\frac{\partial R_{EPI}}{\partial T} = \kappa \frac{\partial(\mu_n^{-1})}{\partial T} \tag{7}$$

where $\kappa = \frac{L_{EPI}}{W_{EPI}} \frac{1}{qN_D t_{EPI}}$

$$\frac{\partial R_{EPI}}{\partial T} \propto \frac{\partial(\mu_n^{-1})}{\partial T} \quad (8)$$

3. Circuit design

The block diagram of the Hall power IC is shown in Figure 1. The Hall power IC detects flow angle and sets the output signal inducing the coil current, applied to 2-phase, half-wave motor drivers. A temperature compensated reference voltage is supplied to the Hall device. The flow angle setting circuit controls the period of current flow in the coil.

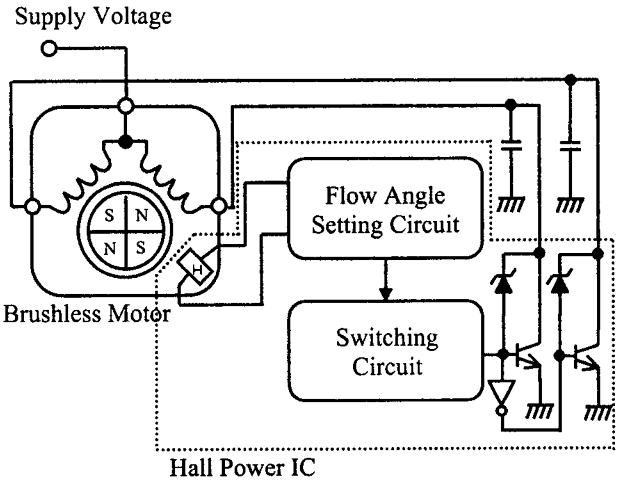

Figure 1. Block diagram of a Hall power IC.

The temperature compensated flow angle setting circuit and switching circuit are shown in Figure 2. Since the Hall voltage is relatively small (18.7μV at 1 Gauss on the average), the signals are amplified through the differential amplifier consisted of transistors $Q_1 \sim Q_3$ and temperature compensating resistor R_{EPI}.

Assume that the amplifier operates in linear range, the voltage difference between V_A and V_B is defined as[4]

$$V_{AB} = \alpha_F I_3 R_{EPI}\left(\frac{-V_{id}}{2V_T}\right) \quad (9)$$

where α_F the effective common-base current gain, I_3 the collector current of Q_3, V_T the thermal voltage, V_{id} the differential input voltage. When the Hall voltage V_H is applied to amplifier, V_{AB} can be expressed as

$$V_{AB} = \alpha_F I_3 R_{EPI}\left(\frac{-V_H}{2V_T}\right) = \alpha_F I_3 B \cdot V_S \cdot R_{EPI}\left(\frac{-S_V}{2V_T}\right) \quad (10)$$

$$V_H = B \cdot V_S \cdot S_V \quad (11)$$

where B is the magnetic field applied to the Hall device. Differentiating Eq.(10) with respect to temperature and yields

$$\frac{\partial V_{AB}}{\partial T} = -\alpha_F I_3 B V_S \times \left[\left(\frac{S_V}{2V_T}\right)\frac{\partial R_{EPI1}}{\partial T} + \left(\frac{R_{EPI1}}{2V_T}\right)\frac{\partial S_V}{\partial T} + \left(\frac{R_{EPI1} S_V}{2}\right)\frac{\partial(V_T^{-1})}{\partial T}\right] \quad (12)$$

In order to compensate the thermal defect, It is desirable to make Eq.(12) near zero as Eq.(13).

$$\frac{\partial V_{AB}}{\partial T} = -\alpha_F I_2 B V_S\left(K_1\frac{\partial R_{EPI}}{\partial T} + K_2\frac{\partial S_V}{\partial T} + K_3\frac{\partial(V_T^{-1})}{\partial T}\right) \cong 0 \quad (13)$$

$\frac{\partial R_{EPI}}{\partial T}$ has the positive value. $\frac{\partial S_V}{\partial T}$ and $\frac{\partial(V_T^{-1})}{\partial T}$ have the negative value. The temperature compensation can be achived by adjusting K_1, K_2 and K_3.

From Figure 2. the output signal V_B of differential amplfier is applied to the positive input of the comparator OP1. V_B is compared with voltage of switching point V_{SP}. V_{SP} has the different value as operating point V_{OP}, release point B_{RP} by hysteresis. V_{OP} and V_{RP} can be expressed as

$$V_{OP} = \frac{V_{REF}(R_{BASE2} + R_{BASE3})}{R_{BASE1} + R_{BASE2} + R_{BASE3}} \quad (14)$$

$$V_{RP} = \frac{V_{REF} R_{BASE2}}{R_{BASE1} + R_{BASE2}} \quad (15)$$

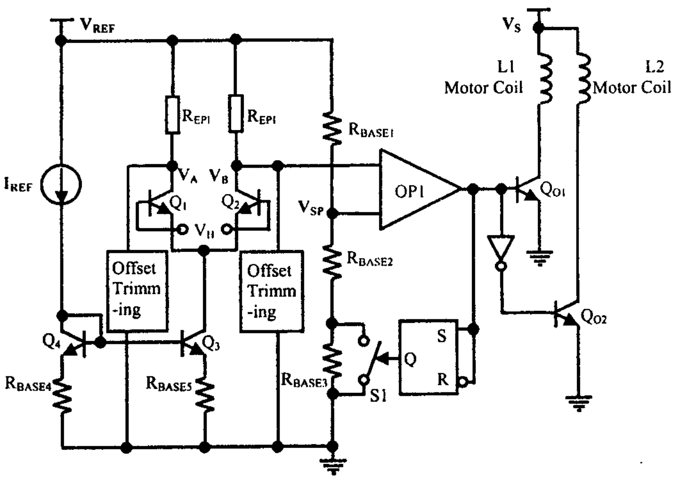

Figure 2. Diagram of flow angle setting circuit and switching circuit.

4. Wafer Processing

The silicon Hall-effect power IC with the Hall device is fabricated using normal standard bipolar IC process. Since the coil is connected to the power transistor's collector, a collector-to-emitter voltage breakdown above 35V is required in PC Fan motor application. To sink current of the motor coil, the power transistors require driving capability of 700 mA, a saturation voltage of 1.0V. Therefore, (100)-oriented p-type wafers with n epi-layers of 3.5Ω·cm resistivity and 11 μm thickness were used. The length and the width of the Hall device are 220 μm and 220 μm, respectively. To decrease the offset voltage the quadrature offset cancellation was used.[5] So four Hall devices with the same shape are connected in parallel, respectively. A schematic cross section of the Hall power IC is shown in Figure 3. The photograph of Hall power IC chip is shown in Figure 4. The chip size is 1100 × 800 μm^2. The Hall voltages at B=100G and Vs=3V range between 1.8mV and 2 mV (typically 1.87 mV) at room temperature.

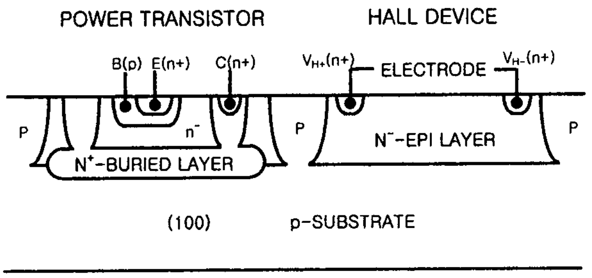

Figure 3. Schematic cross section of the Hall power IC.

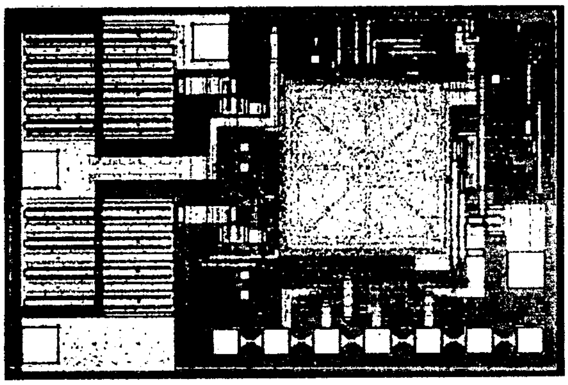

Figure 4. Photograph of Hall power IC chip
(chip size : 1100 × 800 μm^2)

5. Experimental results

The packaged Hall power IC is placed in the small vacuum chamber for temperature test. The vacuum chamber is placed under a large electromagnet. Magnetic field is monitored with Gaussmeter fixed on the electromagnet.

Figure 5 shows the Hall sensitivity under temperature variation. The Hall sensitivity varied from 34μV/G at -40°C to 11 μV/G at 150°C. The variation range of the Hall sensitivity is between –38% ~ 88% according to temperature.

Figure 6 shows the relationship between the Hall voltage and the temperature under 63 G and 27 G of the magnetic field respectively. The Hall voltage decreases nonlinearly when temperature increases.

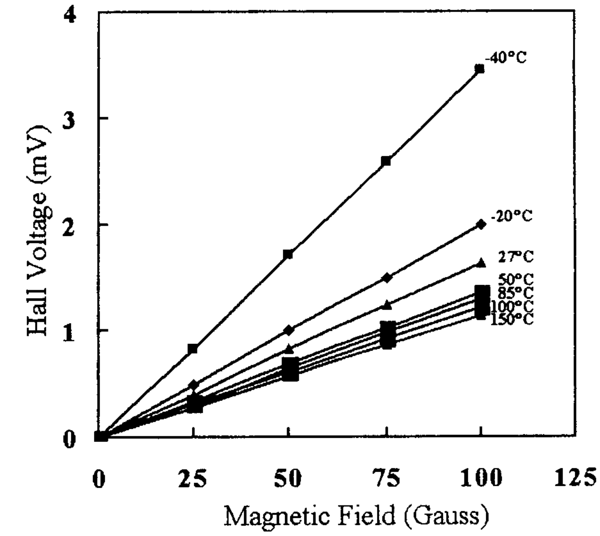

Figure 5. Hall sensitivity according to temperature

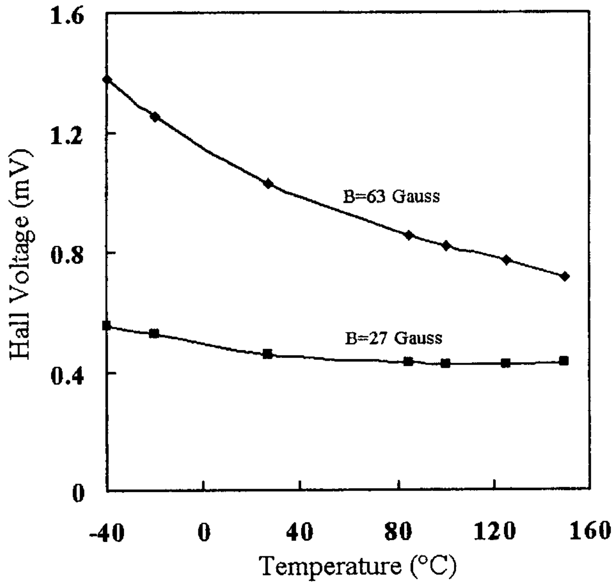

Figure 6. Hall sensitivity variation according to temperature.

Figure 7 shows the Hall voltage generated by the motor rotor(permanent magnet). The rotation speed of the motor is 2727 RPM. The differential output voltage of the Hall device is about 26mV.

Figure 8 shows output waveforms of temperature compensated and uncompensated Hall power IC at 125°C. As the temperature increases the Hall sensitivity deminishs. Without temperature compensation the rotation speed of the motor decreases since the torque decreases.

But with compensation the output waveform nearly keeps ON duty without any torque degeneration.

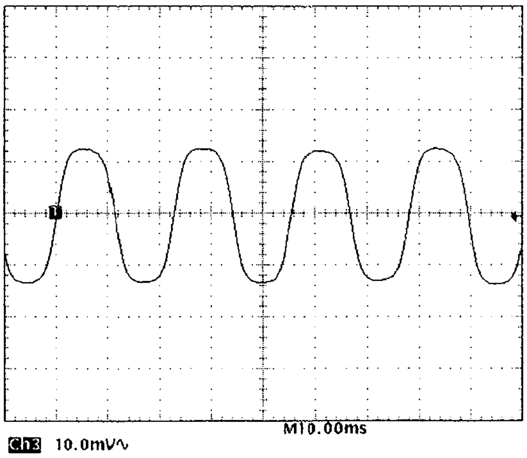

Figure 7. Hall voltage(V_H)generated by the motor rotor (V_H : 10.0mV/div., Time : 10.0ms/div.)

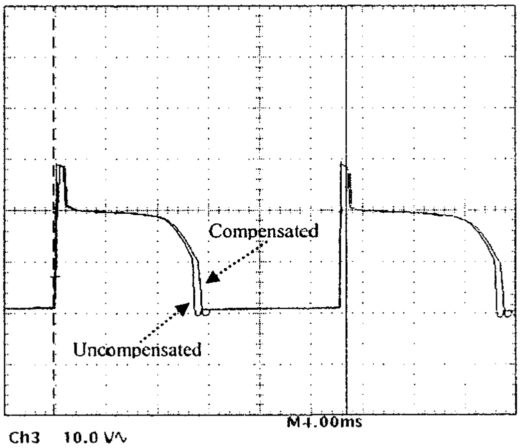

Figure 8. Output waveforms(V_{OUT}) of the Hall power IC (V_{OUT} : 10.0V/div., Time : 4.0ms/div.)

The characteristics of the Hall power IC over temperature are shown in Table 1.

From Table 1, the temperature compensated Hall power IC shows better performance than conventional Hall power IC.

Table 1. The characteristics of the Hall power IC over temperature

Characteristic Item	Hall Power IC			Conventional Hall Power IC			Units
	MIN	TYP	MAX	MIN	TYP	MAX	
Supply Voltage	4.0	12	40				V
Output ON Current	-	-	700	-	-	400	mA
Operating Temperature Range	-40	27	150	0	27	70	°C
Output Saturation Voltage	-	1.0	1.3	-	1.0	1.5	V
Supply Current	-	7	12	-	10	12	mA
Operating Point	30	40	50	15	35	100	G
Release Point	-50	40	-30	-100	35	-15	G

Especially the operating temperature range is wider and the variation of operating point and release point are within ±25%.

6. Conclusion

In this paper the temperature compensated Hall power IC for brushless motor have been presented and realized in a standard bipolar technology, resulting in a very accurate, sensitive and wide-range temperature Hall power IC.

The proposed temperature compensation makes use of in verse temperature characteristics of Hall device and epi-resistor. The Hall sensitivity with negative TC can be compensated by the differential amplifier gain consisted of epi-layer resistor with positive TC. The Hall device has the variations of sensitivity within –38%(at 150°C) ~ 88%(at -40°C). But the operating point(B_{OP}) and release point(B_{RP}) of the Hall power IC are within ±25%.

The incompleteness of compensation is caused by the temperature drift of the offset voltage.

The thermal characteristics of Hall power IC are very stable over a wide temperature range of -40°C to 125°C. The obtained experimental results are in agreement with analytical predictions and have more excellent performance than conventional Hall power IC.

References

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