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Thermal analytic model of current gain for bipolar junction transistor-bipolar static induction transistor compound device*

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This paper proposes a thermal analytical model of current gain for bipolar junction transistor-bipolar static induction transistor (BJT-BSIT) compound device in the low current operation. It also proposes a best thermal compensating factor to the compound device that indicates the relationship between the thermal variation rate of current gain and device structure. This is important for the design of compound device to be optimized. Finally, the analytical model is found to be in good agreement with numerical simulation and experimental results. The test results demonstrate that thermal variation rate of current gain is below 10% in 25 °C–85 °C and 20% in −55 °C–25 °C.

Keywords: bipolar junction transistor-bipolar static induction transistor, thermal analytic model, current gain

PACC: 7340L, 6185

1. Introduction

It is very important that there be electro-thermal stability of a Si device in application to the wide temperature condition or power electronics.[1−4] As a common and widely used device, the bipolar junction transistor (BJT) has a big problem that the current gain increases sharply with the increase of temperature because of the heavy doping effect of the emitter. This confines the application of BJT in the wide temperature condition. The BJT-bipolar static induction transistor (BJT-BSIT) is a compound device regarded as the connection of BJT and BSIT in parallel. It has saturated I–V characteristics the same as the BJT.[5] So it is possible to exchange it with BJT in application. The BJT-BSIT has good thermal stability in the current gain. Experiments have demonstrated that the thermal variation rate of current gain is above 40% in the temperature of −55 °C–85 °C but for BJT-BSIT is below 40% (relative to room temperature).[6] Some theories of BJT-BSIT have been made on I–V characteristics, on-resistance, etc., but there is a lack of theory of the thermal model of current gain.[7−10] We construct the thermal model and also propose a best thermal compensating factor for the compound device that demonstrates the relationship between the thermal variation rate of current gain and the device structure. Finally, the analytical model is found to be in good agreement with numerical simulation and experimental results. This is important for the design to be optimized about wide temperature application for BJT-BSIT.

2. Thermal analytic model of current gain

The simplified cross-sectional view of the BJT-BSIT structure is shown in Fig.1(a). The substrate (collector) of donor concentration is 1e20 cm^{-3}, epitaxial layer is 1e14 cm^{-3} with the depth of 15 μm, source (emitter) of donor concentration is 1e20 cm^{-3} with the depth of 1 μm, base (gate) of acceptor concentration 1e18 cm^{-3} with the depth of $L = 3\,\mu$m. The 'a' is the half channel width and the 'd' is the emitter width of BJT in Fig.1. It works normally-off in the small channel width because of the channel pinched off by the built-in potential of p-n junction. Gate electrode connected to positive voltage V_{G} is approximately 0.7 V, source is to ground, and drain is

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to positive voltage $V_{\rm D}$. $I_{\rm B}$, $I_{\rm C}$ and $I_{\rm E}$ are the current of base, collector and emitter of BJT part respectively; $I_{\rm G}$, $I_{\rm S}$ and $I_{\rm D}$ are the current of gate, source and drain of BSIT part respectively in compound device as shown in Fig.1(b).

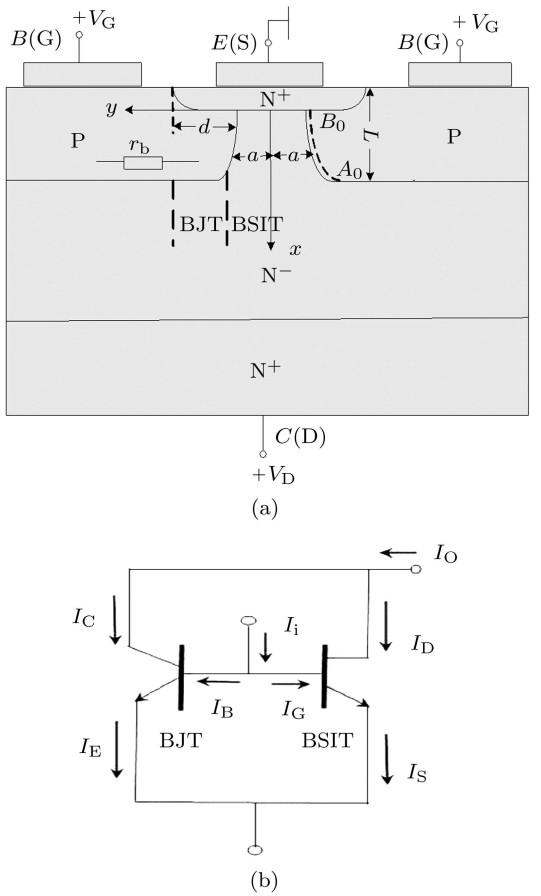


Fig.1. Cross-sectional view and equivalent circuit of BJT-BSIT: (a) cross-sectional view; (b) the equivalent circuit.

We select x-y coordinate on a half structure as cross-sectional view and setup Poisson equation in the depletion region.

$$\frac{\partial^2\phi(x,y)}{\partial x^2}+\frac{\partial^2\phi(x,y)}{\partial y^2}=-\frac{qN_{\rm D}^-}{\varepsilon}. \tag{1}$$

By the principle of potential addition:

$$\phi(x,y)=\phi_{\rm P}(y)+\phi_{\rm L}(x,y), \tag{2}$$

$\phi_{\rm P}(y)$ is the solution of one-dimensional Poisson equation approximating to depletion region. $\phi_{\rm L}(x,y)$ is the solution of two-dimensional Laplace equation by the method of Fourier series. We can obtain the dependence of potential distribution:

$$\begin{aligned}&\phi(x,y)\\&=V_{\rm G}^*-\phi_{\rm P}\left(\frac{y}{a}\right)^2\\&\quad+\left[A\exp\left(-\frac{\pi}{2}\frac{x}{a}\right)+B\exp\left(\frac{\pi}{2}\frac{x}{a}\right)\right]\cos\left(\frac{\pi}{2}\frac{y}{a}\right).\end{aligned} \tag{3}$$

The boundary condition of Eq.(1) is

$$\phi(0,0)=0,\quad \phi(L,0)=V_{\rm D}^*. \tag{4}$$

In Eq.(3):

$$V_{\rm G}^*=V_{\rm G}'-\phi_0 \tag{5}$$

and $\phi_0=\dfrac{kT}{q}\ln\dfrac{N_{\rm D}^+}{N_{\rm D}^-}+\dfrac{kT}{q}\ln\dfrac{N_{\rm A}N_{\rm D}^-}{n_{\rm i}^2}$, namely, built-in potential of source-channel $\rm N^+$-$\rm N^-$ junction and gate-channel p-n junction. The effective gate voltage $V_{\rm G}'$ that distributes on the boundary of gate-channel is the expression: $V_{\rm G}'=V_{\rm G}-I_{\rm i}r_{\rm b}$. Considering that BJT-BSIT has a long source size, we cannot neglect the base resistance. In the experiment, $V_{\rm G}$ is about 0.7 V, gate resistance $r_{\rm b}$ is $200\sim400\,\Omega$ and $I_{\rm i}$ is 1 mA. So we can calculate $V_{\rm G}'$, and get 0.3 V–0.5 V.

From Eqs.(3) and (4), we can get

$$\begin{aligned}A&=\frac{\eta_0}{\eta_0+1}\left(-V_{\rm G}^*-\frac{1}{\eta_0-1}V_{\rm D}^*\right),\\B&=\frac{1}{\eta_0+1}\left(-V_{\rm G}^*+\frac{\eta_0}{\eta_0-1}V_{\rm D}^*\right),\end{aligned} \tag{6}$$

and

$$\eta_0\equiv\exp\left(\frac{\pi L}{2a}\right). \tag{7}$$

Considering $V_{\rm D}^*=0$ in low current application, we can get minimum potential barrier $\phi_{\rm min}$ in the channel:

$$\phi_{\rm min}=(V_{\rm G}'-\phi_0)\left(1+\frac{2\sqrt{\eta_0}}{\eta_0}\right). \tag{8}$$

The research of BSIT has discovered the mechanism of potential barrier dominated below 0.5 V of gate voltage, and we can get the function of $\rm I_D$ in the low current application:[11,12]

$$I_{\rm D}=I_{\rm D0}\exp\left(\frac{q\phi_{\rm min}}{kT}\right). \tag{9}$$

We define the current gain of compound device $h_{\rm FS}$. So we can obtain the expression from Fig.1(b):

$$h_{\rm FS}=\frac{I_{\rm C}+I_{\rm D}}{I_{\rm B}+I_{\rm G}}, \tag{10}$$

and define $h_{\rm FE}=\dfrac{I_{\rm C}}{I_{\rm B}}$, namely, current gain of BJT. Because the effective gate voltage $V_{\rm G}'$ is 0.3 V–0.5 V, there are little holes injecting from gate region to channel. So $I_{\rm G}$ can be taken out of account.

Then we can get

$$\frac{{\rm d}h_{\rm FS}}{h_{\rm FS}{\rm d}T}=\frac{1}{h_{\rm FE}}\frac{{\rm d}h_{\rm FE}}{{\rm d}T}\frac{\dfrac{{\rm d}I_{\rm D}}{I_{\rm D}{\rm d}T}-\dfrac{{\rm d}I_{\rm C}}{I_{\rm C}{\rm d}T}}{\dfrac{I_{\rm C}}{I_{\rm D}}+1}, \tag{11}$$

$$\left.\frac{\mathrm{d}I_\mathrm{D}}{I_\mathrm{D}\mathrm{d}T}\right|_{T=298\,\mathrm{K}} = -0.13V'_\mathrm{G}\left(1+\frac{2\sqrt{\eta_0}}{\eta_0+1}\right) < 0. \quad (12)$$

We also get $\left.\frac{1}{h_\mathrm{FE}}\frac{\mathrm{d}h_\mathrm{FE}}{\mathrm{d}T}\right|_{T=298\,\mathrm{K}} = 0.007/\,^\circ\mathrm{C}$,[13] $\left.\frac{\mathrm{d}I_\mathrm{C}}{I_\mathrm{C}\mathrm{d}T}\right|_{T=298\,\mathrm{K}} = \left.\frac{E_\mathrm{G}-qV_\mathrm{G}}{kT^2}\right|_{T=298\,\mathrm{K}} \approx 0.054/\,^\circ\mathrm{C}$.[14] Suppose $\frac{I_\mathrm{C}}{I_\mathrm{D}} = \frac{\mathrm{Area_{BJT}}}{\mathrm{Area_{BSIT}}}$, namely, the ratio of area BJT and area BSIT. So we can get the dependence:

$$\frac{\mathrm{d}h_\mathrm{FS}}{h_\mathrm{FS}\mathrm{d}T} = 0.007 - \frac{0.13V'_\mathrm{G}\left[1+\frac{2\sqrt{\exp(\pi L/2a)}}{\exp(\pi L/2a)+1}\right]+0.054}{\frac{\mathrm{Area_{BJT}}}{\mathrm{Area_{BSIT}}}+1}. \quad (13)$$

From Eqs.(11,12), we can see that BJT-BSIT is effective on counteracting positive thermal effect of BJT to get the stable current gain under wide temperature condition. By optimizing structure parameters to make $\frac{\mathrm{d}h_\mathrm{FS}}{h_\mathrm{FS}\mathrm{d}T} = 0$, we can get the thermal coefficient of the current gain optimized.

3. Results and discussion

We define the thermal compensating factor to discuss the thermal compensation of compound device.

$$\zeta = \frac{0.13V'_\mathrm{G}\left[1+\frac{2\sqrt{\exp(\pi L/2a)}}{\exp(\pi L/2a)+1}\right]+0.054}{\left(\frac{\mathrm{Area_{BJT}}}{\mathrm{Area_{BSIT}}}+1\right)\cdot 0.007} \quad (14)$$

$\xi = 1$, $\frac{\mathrm{d}h_\mathrm{FS}}{h_\mathrm{FS}\mathrm{d}T} = 0$, it is the best thermal compensating coefficient for BJT-BSIT; $\xi > 1$, $\frac{\mathrm{d}h_\mathrm{FS}}{h_\mathrm{FS}\mathrm{d}T} < 0$, it is the negative thermal compensating coefficient for BJT-BSIT; $0 < \xi < 1$, $\frac{\mathrm{d}h_\mathrm{FS}}{h_\mathrm{FS}\mathrm{d}T} > 0$, it is the positive thermal compensating coefficient for BJT-BSIT.

We can see from Fig.2 that it is the negative thermal compensating region in the left of $\xi = 1$. It is the reason that BJT current is the smaller part in the compound device because of the smaller Area(BJT)/Area (BSIT). However $\left.\frac{\mathrm{d}I_\mathrm{C}}{I_\mathrm{C}\mathrm{d}T}\right|_{T=298\,\mathrm{K}}$ of BJT is positive and $\left.\frac{\mathrm{d}I_\mathrm{D}}{I_\mathrm{D}\mathrm{d}T}\right|_{T=298\,\mathrm{K}}$ of BSIT is negative. So comparing with the best thermal compensating point, it presents the negative thermal compensating characteristics. Similarly it is the positive thermal compensating characteristics in the right of $\xi = 1$. Figure 2 also indicates ξ increasing with the increase of V'_G at the same Area(BJT)/Area(BSIT). The explanation is that the potential barrier of channel for BJT-BSIT decreases obviously with the increase of V'_G. So it induces I_D increasing obviously in comparison with the same I_C at the certain drain voltage. The compound device presents the negative thermal compensating characteristics.

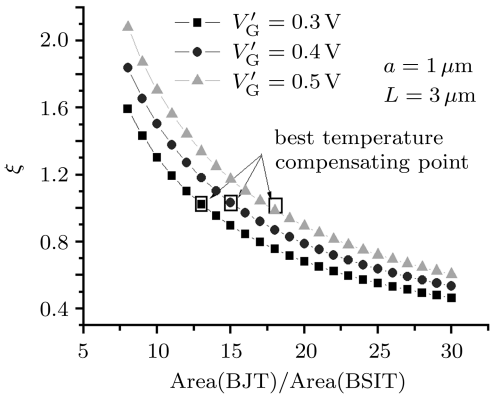


Fig.2. Dependences of thermal compensating factor with the different ratios of area (half channel width $a = 1\,\mu$m, diffusion depth $L = 3\,\mu$m).

Figure 3 demonstrates that Area(BJT)/Area (BSIT) increases first and then tends to saturation with the increase of channel width under the best thermal compensating condition. When the half channel width changes from $a = 1\,\mu$m to $a = 4\,\mu$m, the potential barrier decreases and I_D increases obviously. To maintain the best thermal compensation, it is necessary to increase Area(BJT)/Area(BSIT), namely, increase I_C. When the channel width $a > 4\,\mu$m, p-n junction of gate-channel cannot be pinched off by the depletion area. So the compound device is not normally–off and I_D tends to saturation on the drain voltage V_D, namely, Area(BJT)/Area(BSIT) tends to saturation.

The authors utilize the simulation software TCAD MEDICI to certify the thermal model. We simulate the dependences of ξ and Area(BJT)/Area(BSIT) in comparison with the analytic model and get Fig.4. It must account for the fact that Area(BJT)/Area(BSIT) in 2-D simulation is the ratio of d/a (as shown in Fig.1).

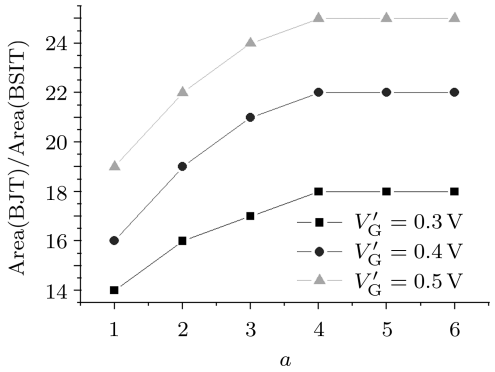


Fig.3. Dependences of different ratios of area with different half channel width on the best thermal compensating condition ($\xi = 1$).

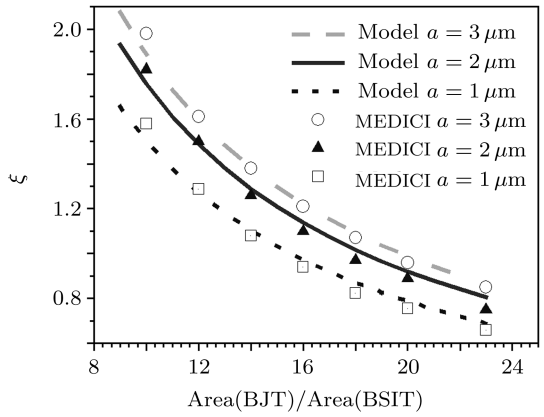


Fig.4. Comparison of proposed model and MEDICI simulation on the conditions of $a = 1\,\mu$m, $2\,\mu$m, $3\,\mu$m and $V'_G = 0.4$ V.

We design the structure and the process parameters of BJT-BSIT based on the best thermal compensation condition, namely, $a = 1\,\mu$m and Area(BJT)/Area(BSIT) = 16, $a = 2\,\mu$m and Area(BJT)/Area(BSIT) = 19, $a = 3\,\mu$m and Area(BJT)/Area(BSIT) = 21. We also make different cells of layout with square, donut and compounding square as shown in Fig.5, then do experiments and test samples of current gain variation rate and I–V characteristics as shown in Fig.6. Thermal variation rate of current gain testing for high (25 °C–85 °C) and low (−55 °C–25 °C) temperature are the dependences:

$$\theta_1 = \left| \frac{h_{\mathrm{FS}\ (T=358\,\mathrm{K})} - h_{\mathrm{FS}\ (T=298\,\mathrm{K})}}{h_{\mathrm{FS}\ (T=298\,\mathrm{K})}} \right|, \quad (15)$$

$$\theta_2 = \left| \frac{h_{\mathrm{FS}\ (T=218\,\mathrm{K})} - h_{\mathrm{FS}\ (T=298\,\mathrm{K})}}{h_{\mathrm{FS}\ (T=298\,\mathrm{K})}} \right|. \quad (16)$$

We can also get the dependences of thermal variation rate of current gain and thermal compensating factor:

$$\xi_{1(2)} = \left[0.007 - \frac{\theta_{1(2)}}{\Delta T} \right] \Big/ 0.007. \quad (17)$$

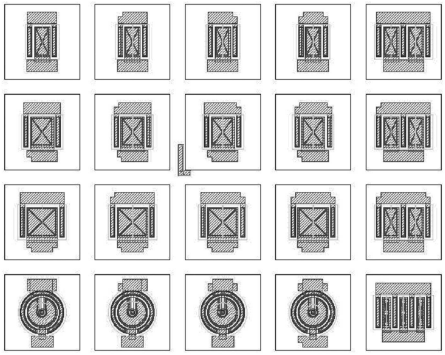


Fig.5. Different cells with square, donut and compounding square based on the model.

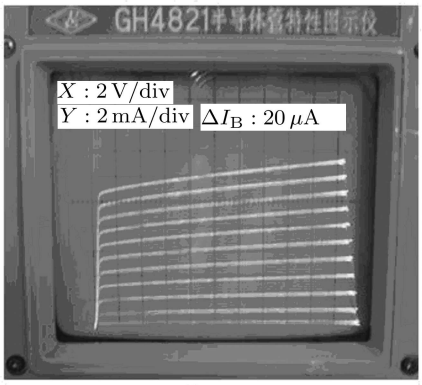


Fig.6. BJT-BSIT I–V characteristics curve.

The test results demonstrate that the thermal variation rate of current gain is below 10% in 25 °C–85 °C and 20% in −55 °C–25 °C in Table 1. It is much better than thermal variation rate of BJT current gain 0.007/ °C to achieve compensation effectively. But we can also see that test results depart from the best thermal compensating condition: $\xi = 1$. It is the reason why the process error departs from the channel width optimized, such as time and temperature of gate's diffusing process. Otherwise, the cryogenic effect of BJT is not considered, which results in the test results in the low temperature more away $\xi = 1$ than in the high temperature.[15]

Table 1. Test results of current gain variation rate for high temperature θ_1 and low temperature θ_2 and the corresponding thermal compensating factor ξ_1 and ξ_2.

	θ_1	ξ_1	θ_2	ξ_2
$a = 1$	7.1%	0.83	13.4%	0.76
$a = 2$	7.8%	0.81	14.0%	0.75
$a = 3$	8.2%	0.80	16.1%	0.71

4. Conclusion

BJT-BSIT is a compound device with the same I–V characteristics as BJT. At the same time, BJT-BSIT has the advantage of stable thermal characteristics of current gain. So it is possible to exchange with BJT in wide temperature application.

A thermal analytical model of current gain for BJT-BSIT in low current operation is proposed. We setup the thermal model and also propose a best thermal compensating factor that indicates the relationship between the thermal variation rate of current gain and the device structure.

We design the structure and the process parameters of BJT-BSIT based on the best thermal compensation, namely, $a = 1\,\mu$m and Area(BJT)/Area(BSIT) = 16, $a = 2\,\mu$m and Area(BJT)/Area(BSIT) = 19, $a = 3\,\mu$m and Area (BJT)/Area (BSIT) = 21. The simulation results match with the model.

The test results demonstrate that the thermal variation rate of current gain is below 10% in 25 °C–85 °C and 20% in −55 °C–25 °C. This is much better than the thermal variation rate of BJT current gain 0.007/ °C to achieve the thermal compensation effectively.

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