Analytical Model for Electrical and Thermal Transients of Self-Heating Semiconductor Devices

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***Abstract*—Transients of self-heating semiconductor devices are theoretically investigated based on a feedback circuit model, which is composed of three sub-circuits describing the isothermal electrical characteristics, thermal impedance, and temperature dependence of the electrical characteristics of the devices, respectively. Analytical expressions of the frequency and transient responses have been derived for both the electrical and thermal characteristics of self-heating devices, yielding accurate methods to extract the thermal time constant in both the time and frequency domains. The model is verified by the transient electrical-response measurement of a GaInP/GaAs heterojunction bipolar transistor.**

***Index Terms*—Feedback, heterojunction bipolar transistor, microwave device, MMIC's, semiconductor device modeling, semiconductor device thermal factors, transient analysis.**

I. Introduction

The transient thermal effect must be accounted for if the high-frequency and switching performance of self-heating semiconductor devices is to be accurately modeled. This applies particularly to GaAs-based and silicon-on-insulator (SOI) devices, where the self-heating effect is enhanced by the low thermal conductivity of the GaAs substrate in GaAs-based devices and the low thermal conductivity of the back oxide in SOI devices. Investigation of transient thermal effects in AlGaAs/GaAs heterojunction bipolar transistors (HBT's) and SOI MOSFET's, for example, have been reported [1]–[4].

Two kinds of models, the physical and the circuit models, have previously been proposed to describe the transient response of self-heating devices. The physical model is based on simultaneous calculation of the current and heat flow inside the devices [5], [6], and the circuit model is realized by adding thermal sub-circuits, including explicit temperature dependence of model parameters [5]–[11]. Both of the models lead, however, to either complicated analytical expressions or numerical-only results. While analytical expressions have been reported for HBT's under a specific operating state [12], [13], no such expressions are available for the general case of self-heating devices. Explicit analytical expressions describing the transients of self-heating devices are of concern to device characterization and model parameter extraction.

In this paper, explicit analytical expressions of the transients of self-heating devices are derived based on a proposed feedback circuit model. In Section II, the frequency response of self-heating devices are derived. The transient electrical and thermal responses of self-heating devices are derived in Section III and are applied in Section IV to extract the thermal time constant from the measured transient electrical response of InGaP/GaAs HBT's. The results obtained are summarized in Section V.

Our results describe for the first time: 1) both the frequency response and the transient response for the general case of self-heating devices including bipolar junction transistors (BJT's), HBT's, MOSFET's, MESFET's and high electron-mobility transistors (HEMT's); 2) the transients in both thermally stable and unstable states; and 3) the transients due to both negative and positive thermal feedback. These results can be used to extract the model parameters and thermal time constant, for example, in both the time and frequency domains.

II. Frequency Response of Self-Heating Devices

The self-heating effect, caused by the temperature rise due to the power dissipation and the temperature dependence of device characteristics, can be regarded as a thermal-electrical feedback inside the device [14]. The feedback can either be negative or positive depending on the kind of device and operating state of the device. In the case of an HBT with a grounded emitter, for example, the feedback is negative (positive) when a constant base current (voltage) is applied [15]. and the amount of the thermal feedback is dependent on the dissipated power.

The block diagrams of the proposed feedback circuit models, which describe the electrical and thermal behaviors of self-heating devices, are shown in Figs. 1 and 2. Here, x and y denote the input and output signals, respectively, and ΔT is the temperature rise inside the device. The sub-circuit $g(\omega)$ represents the isothermal gain of the device, and the sub-circuit $Z(\omega)$, called thermal impedance, describes the temperature rise due to power dissipation. The temperature dependence of the electrical characteristics is described in terms of the change in the overall circuit, as in previous circuit models, but is described in terms of the equivalent change in the

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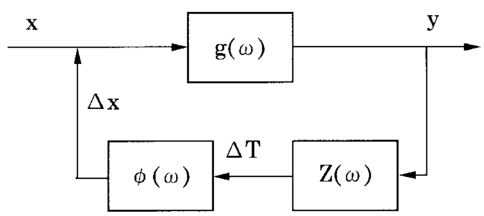

Fig. 1. Feedback-model block diagram of self-heating device for electrical characteristics.

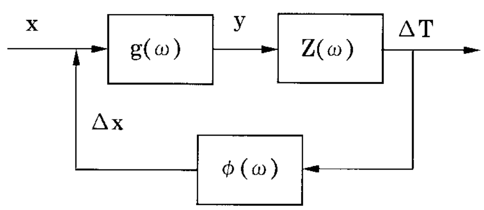

Fig. 2. Feedback-model block diagram of self-heating device for thermal characteristics.

signal by way of the sub-circuit $\phi(\omega)$, which is called the thermal-electrical feedback coefficient.

According to Figs. 1 and 2, the frequency response of the electrical and thermal characteristics of self-heating device can easily be derived as

$$G(\omega) = \frac{g(\omega)}{1 - g(\omega)Z(\omega)\phi(\omega)} \tag{1}$$

and

$$H(\omega) = \frac{g(\omega)Z(\omega)}{1 - g(\omega)Z(\omega)\phi(\omega)} \tag{2}$$

respectively.

The isothermal gain refers to, for example, the current gain of HBT's, transconductance of MOSFET's, or power gain of a two-port device, and can be expressed as [16]

$$g(\omega) = g_0/(1 + j\omega\tau_g) \tag{3}$$

where $g_0 = (\partial y/\partial x)|_{\omega=0}$ and $1/\tau_g$ corresponds to the electrical cutoff frequency.

The thermal impedance $Z(\omega)$ is usually modeled using an *RC* ladder circuit, which is biased by a current proportional to the power dissipation of the devices and generates a voltage though the *RC* ladder equal to the temperature rise. When a single-pole *RC* ladder circuit is used, $Z(\omega)$ can be expressed as [17], [18]

$$Z(\omega) = R_{\rm th}/(1 + j\omega\tau_{\rm th}) \tag{4}$$

where $R_{\rm th} = (\partial T/\partial P_o)|_{\omega=0}$ is called the thermal resistance, and $\tau_{\rm th} = R_{\rm th}C$ the thermal time constant, and C the thermal capacitance, respectively. $R_{\rm th}$ can be extracted from the temperature dependence of the dc electrical characteristics [19], [20].

While the dc behavior of the thermal–electrical feedback coefficient ϕ has been reported [21], neither the frequency nor the transient response of ϕ has been investigated. Since the time constant for $\phi(\omega)$ is believed to be determined by the electron scattering rate and is on the order of picoseconds [22], and is thus negligible compared with the thermal time constant of devices, the thermal–electrical feedback coefficient is assumed to be independent of frequency in this study as

$$\phi(\omega) = \phi_0 \tag{5}$$

where ϕ_0 is the dc value of $\phi(\omega)$.

The frequency responses of the electrical and thermal characteristics of the devices can be obtained by substituting (3)–(5) into (1) and (2), respectively, and can further be simplified as

$$G(\omega) = \frac{g_0}{1 - f/(1 + j\omega\tau_{\rm th})} = \begin{cases} g_0\left\{1 + \dfrac{f}{1-f}\,\dfrac{1}{[1 + j\omega\tau_{\rm th}/(1-f)]}\right\}, & f \neq 1 \quad (6) \\ g_0\left(1 + \dfrac{1}{j\omega\tau_{\rm th}}\right), & f = 1 \quad (7) \end{cases}$$

and

$$H(\omega) = \frac{g_0 R_{\rm th}}{1 - f + j\omega\tau_{\rm th}} = \begin{cases} \dfrac{g_0 R_{\rm th}}{(1-f)[1 + j\omega\tau_{\rm th}/(1-f)]}, & f \neq 1 \quad (8) \\ g_0 R_{\rm th}/j\omega\tau_{\rm th}, & f = 1 \quad (9) \end{cases}$$

respectively, since $\tau_{\rm th} \gg \tau_g$ holds for BJT's, HBT's, MOSFET's, MESFET's, and HEMT's. Here, $f = g_0 R_{\rm th}\phi_0$ is the dc loop gain of the feedback circuit.

When $f < 1$, (6) can be rewritten as

$$G(\omega) = G_b + (G_l - G_h)\,\frac{1}{[1 + j\omega\tau_{\rm th}(G_l/G_h)]} \tag{10}$$

where $G_l = (\beta_0/1 - f)$ $(G_h = \beta_0)$ is the gain of the device in the frequency range of $\omega \ll 1/\tau_{\rm th}$ $(1/\tau_{\rm th} \ll \omega \ll 1/\tau_\beta)$ by considering (neglecting) the self-heating. Since the frequency at the 3-dB point of the frequency response does not correspond directly to $\tau_{\rm th}$, as shown in (10), the method to extract $\tau_{\rm th}$ in frequency domain proposed by Bruce *et al.* [23] should thus be modified.

III. Transient Response of Self-Heating Devices

The transient electrical response of a self-heating device in response to a step input can be obtained from the inverse Laplace transform [24] of (6) and (7) as

$$y(t) = \begin{cases} g_0 x\left\{1 + \dfrac{f}{1-f}\left[1 - \exp\left(-\dfrac{t}{\tau_{\rm th}/(1-f)}\right)\right]\right\}, & f \neq 1 \quad (11) \\ g_0 x(1 + t/\tau_{\rm th}), & f = 1 \quad (12) \end{cases}$$

The transient electrical responses calculated using (11) and (12) are shown in Fig. 3. The device is stable when $f < 1$, the electrical output decreases (increases) with time during the transient and the response becomes faster (slower) with the increasing the amount of the negative (positive) feedback. The device becomes unstable and may be destroyed by thermal

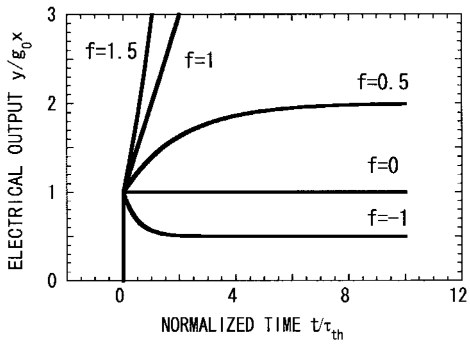

Fig. 3. Calculated transient electrical responses of a self-heating device.

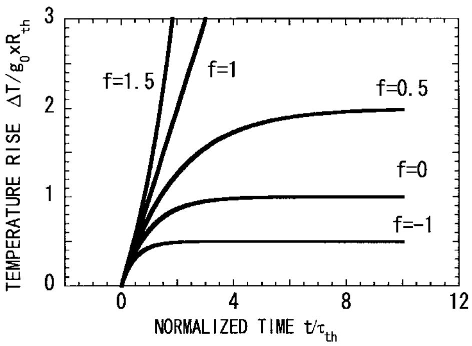

Fig. 4. Calculated transient thermal responses of self-heating device.

runaway [25] when $f_1 \geqq 1$, and the output increases linearly (exponentially) with time for $f = 1$ $(f > 1)$.

In a similar way, the transient thermal response can be obtained from the inverse Laplace transform of (8) and (9) as

$$\Delta T(t) = \begin{cases} \dfrac{g_0 R_{\rm th} x}{1-f}\left[1 - \exp\left(-\dfrac{t}{\tau_{\rm th}/(1-f)}\right)\right], & f \neq 1 \quad (13) \\ g_0 R_{\rm th} x\, \dfrac{t}{\tau_{\rm th}}, & f = 1 \quad (14) \end{cases}$$

The transient thermal responses calculated using (13) and (14) are shown in Fig. 4. It is interesting to note the differences between the transient thermal and transient electrical responses. For the negative feedback, namely $f < 0$, the temperature inside the devices increases and the electrical output decreases during the transient. When $f = 0$, there is no correlation between the transient electrical and thermal responses, and the electrical (thermal) response is determined by the time constant τ_g $(\tau_{\rm th})$ only.

IV. Transient Measurement of GaInP/GaAs HBT

When the device is stable $(f < 1)$, (11) can be rewritten as

$$y(t) = y_i + (y_s - y_t)\left\{1 - \exp\left[-\frac{t}{\tau_{\rm th}(y_s/y_i)}\right]\right\} \quad (15)$$

where $y_i = g_0 x$ $(y_s = (g_0 x/1 - f)$ in (15) is the electrical output at the initial (steady) state of the electrical transient, where the self-heating effect is negligible (strong). Taking the exponential factor of $y(t) \propto [1 - \exp(-t/\tau)]$ as $\tau_{\rm th}$ [12] may underestimate (overestimate) the thermal time constant for negative (positive) thermal–electrical feedback. An expression similar to (15) was derived by Suh *et al.* in the time domain for HBT's with negative feedback [13]. In a similar way, (13) can also be rewritten as

$$\Delta T(t) = \Delta T_f\left\{1 - \exp\left[-\frac{t}{\tau_{\rm th}(\Delta T_f/\Delta T_0)}\right]\right\} \quad (16)$$

for $f < 1$. Here, ΔT_0 (ΔT_f) in (16) is the temperature rise inside the device for $f = 0$ $(f \neq 0)$.

Using (11), (13), and (15), the transient electrical and thermal responses can related as

$$\Delta T(t) = \frac{y(t) - y_i}{y_s - y_i}\, y_s R_{\rm th}, \qquad f < 1 \text{ and } f \neq 0 \quad (17)$$

namely, the transient temperature rise inside the device can be calculated from the transient electrical response.

From the viewpoint of curve fitting, (15) and (16) can be expressed as $y(t) = C_1 + C_2[1 - \exp(-t/C_3)]$ and $\Delta T(t) = C_4[1 - \exp(-t/C_5)]$, respectively, and the fitting parameters, which can be determined by curve fitting, are C_1, C_2, and C_3 for electrical response, and are C_4 and C_5 for thermal response. y_i, y_s, and $\tau_{\rm th}$ can be calculated from the three fitting parameters C_1, C_2, C_3, while ΔT_0, ΔT_f, $\tau_{\rm th}$ cannot be calculated only from C_4 and C_5. In other words, the thermal time constant cannot be extracted, in principle, only from the transient thermal response.

The transient electrical response measurement is easy to perform and yields sufficient information to extract thermal time constant. The transient electrical response was measured on a GaInP/GaAs HBT with an emitter size of 2.4×20 μm^2 using the setup shown in Fig. 5. The transient electrical response of the HBT under pulsed base–emitter voltage and dc collector–emitter voltage is shown in Fig. 6. The dots are the mea-

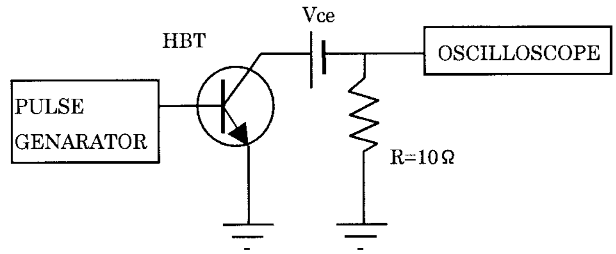

Fig. 5. Setup for measuring transient electrical response of HBT.

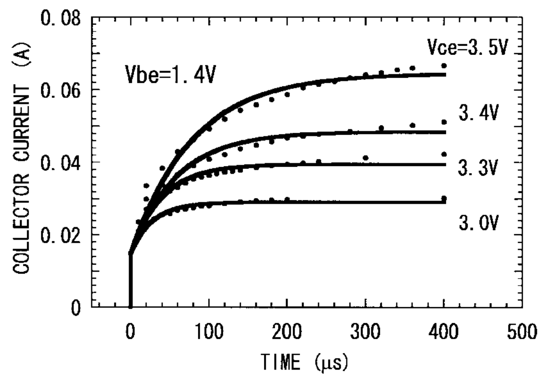

Fig. 6. Measured transient electrical response of HBT under pulsed V_{be}.

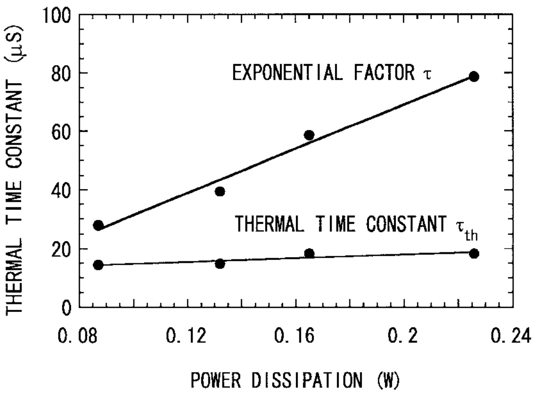

Fig. 7. Extracted thermal time constant versus power dissipation.

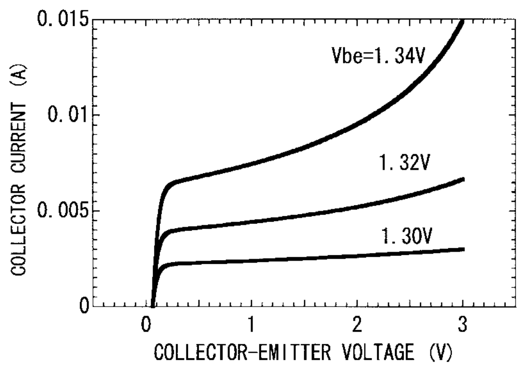

Fig. 8. Measured dc I_c–V_{ce} characteristics of an HBT.

sured responses and the lines are the fitting curves using (15). Due to the positive thermal feedback, an increase in the collector current with time during the transient can be observed.

Fig. 7 shows the dissipated power dependence of τ extracted using $y(t) \propto [1 - \exp(-t/\tau)]$, which can be regarded as a figure-of-merit of the response speed. The increase in τ with increasing dissipated power, which is the slowing of the thermal response with increasing the positive feedback, was confirmed experimentally for the first time. Superimposed on the plot are the thermal time constants extracted using (15), and the thermal time constants extracted this way give an average value of $\tau_{\rm th} = 16$ μs. The differences between τ and $\tau_{\rm th}$ in Fig. 7 indicate the error in the conventional method [12].

The dc I_c-V_{ce} characteristics of the HBT measured with constant V_{be} using an HP4155 parameter analyzer is shown in Fig. 8. Since the HBT is set at each bias point for milliseconds, the measurement is thus performed when the device is in steady state. The increase in I_c with increasing V_{ce} due to the positive thermal–electric feedback can be observed. Based on the dc I_c–V_{ce} characteristics and the thermal time constant extracted, the transient electrical responses at various bias points can be predicted using (15). The predictions of Fig. 9 clearly shows the relation between the transient response and dc characteristics.

V. Conclusion

A feedback circuit model has been proposed to describe the self-heating in semiconductor devices, and the thermal–electrical feedback inside the device is described by an equivalent change in input signal. Analytical expressions of frequency and transient responses have been derived for both electrical and thermal characteristics. A simple method to extract the thermal time constant from the transient electrical response has been proposed. The dependence of the thermal response speed on the thermal feedback was confirmed, and the thermal time constant $\tau_{\rm th} = 16$ μs was extracted for μm^2 GaInP/GaAs HBT's.

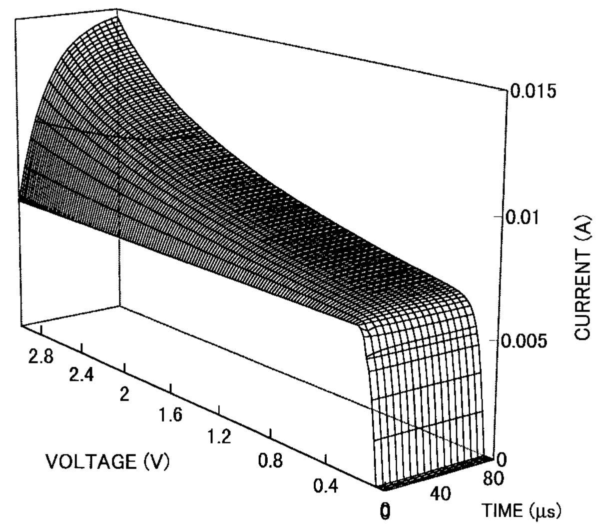

Fig. 9. Transient electrical responses at various bias points.

References

[1] P. Grossman, and J. Choma, "Large signal modeling of HBT's including self-heating and transit time effects," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 449–463, 1992.

[2] K. Lu, P. McIntosh, C. Snowden, and R. Pollard, "Low-frequency dispersion and its influence on the intermodulation performance of AlGaAs/GaAs HBT's," in *IEEE MTT-S Dig.* , 1996, pp. 1373–1376.

[3] G. Workman, J. Fossum, and M. Pelella, "Physical modeling of temperature dependence of SOI CMOS devices and circuits including self-heating," *IEEE Trans. Electron Devices*, vol. 45, pp. 125–133, 1998.

[4] B. Tenbroek, M. Lee, W. Redman-White, R. Bunyan, and M. Uren, "Self-heating effects in SOI MOSFET's and measurement by small signal conductance techniques," *IEEE Trans. Electron Devices*, vol. 43, pp. 2240–2248, 1996.

[5] R. Joy, and E. Schlig, "Thermal properties of very fast transistors," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 586–594, 1970.

[6] Y. Min, A. Palisoc, and C. Lee, "Transient thermal study of semiconductor devices," *IEEE Trans. Comp., Hybrids, Manuf. Technol.*, vol. 13, pp. 980–988, 1990.

[7] A. Chryssafis and W. Love, "A computer-aided analysis of one-dimensional thermal transients in n-p-n power transistors," *Solid State Electron.*, vol. 22, pp. 249–256, 1979

[8] S. Clemente, "Transient thermal response of power semiconductor to short power pulse," *IEEE Trans. Power Electron.*, vol. 8, pp. 337–341, 1993.

[9] Z. Hu. P. Mawby, M. Towers, and K. Board, "Simulation of transient self-heating during power VDMOS transistor turn-off," *Int. J. Electron.*, vol. 77, pp. 525–534, 1994.

[10] T. Peyretaillade, M. Perez, S. Mons, R. Sommet. Ph. Auxemery, J. Lalaurie, and R. Quere, "A pulsed-measurement based electrothermal model of HBT with thermal stability prediction capabilities," in *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1515–1518, 1997.

[11] H. Yamaguchi, H. Himi, S. Akita, and T. Morishita, "Analysis of self-heating in SOI high voltage MOS transistor," *IEICE Trans. Electron.*, vol. E80-C, pp. 423–430, 1997.

[12] P. Baureis, D. Seitzer, and U. Schaper, "Modeling of self-heating in GaAs/AlGaAs HBT's for accurate circuit and device analysis," in *GaAs IC Symp.*, 1991, pp. 125–128.

[13] Y. Suh, T. Roh, Y. Kim, J. Shin, and B. Kim, "A novel extraction method for temperature dependent large signal equivalent circuit model of HBT," in *27th Eumc*, Sept. 1997, pp. 97–103.

[14] J. Sparkes, "Voltage feedback and thermal resistance in junction transistors," *Proc. IRE*, vol. 46, pp. 1305–1306, 1958.

[15] Q. Zhang, H. Hu, J. Sitch, R. Surridge, and J. Xu "A new large signal HBT model," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2001–2009, 1996.

[16] S. M. Sze, *Physics of Semiconductor Devices*. New York: Wiley, 1981.

[17] P. Munro and F. Ye, "Simulation of current mirror with a self-heating BJT model," *IEEE J. Solid-State Circuits*, vol. 26, pp. 1321–1324, 1991.

[18] D. Zweidinger, R. Fox, J. Brodsky, T. Jung, and S. Lee, "Thermal impedance extraction for bipolar transistors," *IEEE Trans. Electron Devices*, vol. 43, pp. 342–346, 1996.

[19] D. Dawson, A. Gupta, and M. Salib, "CW measurement of HBT thermal resistance," *IEEE Trans. Electron Devices*, vol. 39, pp. 2235–2239, 1992.

[20] J. Waldrop, K. Wang, and P. Asbeck, "Determination of junction temperature in AlGaAs/GaAs heterojunction bipolar transistors by electrical measurement," *IEEE Trans. Electron Devices*, vol. 39, pp. 1248–1250, 1992.

[21] W. Liu and A. Yuksel, "A survey of thermal-electric feedback coefficients in GaAs-based heterojuntion bipolar transistors," *Solid State Electron.*, vol. 38, pp. 407–411, 1995.

[22] K. Tomizawa, *Numerical Simulation of Submicron Semiconductor Devices*. Norwood, MA: Artech House, 1993.

[23] S. Bruce, A. Trasser, M. Birk, A. Rydberg, and H. Schumacher, "Extraction of thermal time constant in HBT's using small signal measurements," *Electron. Lett.*, vol. 33. pp. 165–166, 1997.

[24] J. Vegte, *Feedback Control System*. Englewood Cliffs, NJ: Prentice-Hall, 1994.

[25] L. Liou, B. Bayraktaroglu, and C. Huang, "Theoretical thermal runaway analysis of heterojunction bipolar transistors: Junction temperature rise threshold," *Solid State Electron.*, vol. 39, pp. 165–172, 1996.

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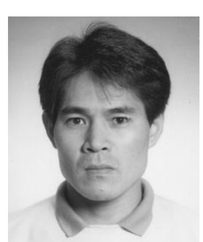

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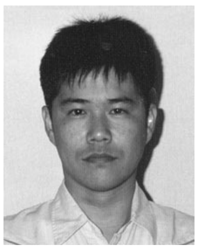

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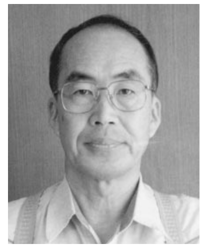

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