MEXTRAM Modeling of Si-SiGe HPTs

Feng Yuan, *Student Member, IEEE*, Jin-Wei Shi, Zingway Pei, and Chee Wee Liu, *Senior Member, IEEE*

Abstract—The integration of the photodetector is essential for optical communication chips. The heterojunction phototransistor (HPT) is integrable with the SiGe HBT process and can be modeled by a modified MEXTRAM model for the circuit simulation. The impact ionization to obtain an extra gain for the optoelectronic conversion and the “early voltage reduction” under constant illumination are well modeled in a modified model. The base recombination current (nkT current) and the substrate contact to enhance the HPT speed are incorporated in ac model. It shows a good agreement between measurement and simulation.

Index Terms—Heterojunction phototransistor (HPT), MEXTRAM, nkT recombination current, photodetector, SiGe.

I. INTRODUCTION

THE HETEROJUNCTION phototransistor (HPT) can be used in the front end of the optical receiver for the optoelectronic integrated circuits (OEICs). To date, most photodetectors (PDs) are based on III-V materials due to the weak light absorption of Si. However, the III-V-based PDs [1]–[3] are hard to integrate on Si and increase the cost of the hybrid circuits. In order to overcome the drawback of the weak photoabsorption process in Si material and the problems in system integration of III-V-based PDs, the Si-SiGe HPT with 850-nm absorption has been demonstrated [4], [5]. However, to integrate this phototransistor into the Si-based receiver circuit for optical communication, not only is the compatible process a prerequisite [4], [5], but also the device model is required for the circuit design. A Gummel–Pool model has been used for HPTs [6], [7] with inherited disadvantages such as the lack of impact ionization model, the uncertainty in the quasi-saturation region, and the inaccuracy of the cutoff frequency. The impact ionization can amplify the photocurrent, and it is important to model the near-breakdown region in the device simulation. The designed base recombination current at the depletion of the B–E junction (nkT current) provides a possible bias margin for avalanche gain and can increase the speed of the HPTs. The strong current dependence on breakdown voltage BV_{CE} due to the nkT base

Fig. 1. Cross section of the Si-SiGe HPT. For the MQW devices, the MQW is sandwiched between the base and collector. For the regular devices, there are no such MQWs.

current is modeled. The compact model for HPTs also has to incorporate the transient simulation including the diffusion, drift, and nkT recombination of the photogenerated holes when light is switched off. In this paper, we present a modified MEXTRAM model¹ [8], [9] for the HPT simulation. This modified model includes: 1) the current sources to model the photocurrent generated between the base-collector and the collector-substrate junctions; 2) the voltage dependency on the photocurrent to model the “early voltage reduction” under constant illumination; 3) the interplay between BV_{CE} , nkT base recombination current, and avalanche multiplication to model an extra photogain due to the impact ionization; and 4) the substrate contact effect to model the impulse response of the HPT. Both the regular device and the HPTs with multiple quantum wells (MQWs) between the base and the collector can be modeled. Note that the extra light absorption of MQWs can extend the cutoff wavelength beyond 1.1 μm and increase the absorption efficiency at 850 nm [4], [5].

II. EXPERIMENT

The cross section of the modeled Si-SiGe HPT is shown in Fig. 1, and the HPT is essentially a four-terminal device, including the emitter (E), the base (B), the collector (C), and the substrate contact (S). There are two kinds of the HPTs. The MQW device has the unintentionally doped Si-Si_{0.5}Ge_{0.5} multiple quantum wells grown between the base and the collector, and the commercial HBT device does not. The multiple

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F. Yuan is with the Graduate Institute of Electronics Engineering and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.

J.-W. Shi is with the Department of Electrical Engineering, National Central University, Taoyuan, Taiwan, R.O.C.

Z. Pei is with the Electronic Research and Service Organization /ITRI, Hsinchu, Taiwan, R.O.C.

C. W. Liu is with the Graduate Institute of Electronics Engineering and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R. O. C., and also with the Electronic Research and Service Organization/ITRI, Hsinchu, Taiwan, R.O.C. (e-mail:chee@cc.ee.ntu.edu.tw).

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¹The MEXTRAM model was developed by Philips Electronics N.V. and is public domain since 1994.

Fig. 2. Equivalent circuit of the HPT used in SPICE. The photocurrent is modeled as the two current sources at the collector-base and the collector-substrate junctions. They are a function of V_{CB} and V_{SC} , respectively.

quantum wells are used to improve the absorption efficiency of light. The SiGe base of the MQW device consists of an unintentionally doped 30-nm Si layer, a 30-nm SiGe-graded layer with Ge = 0% to 15% and a boron concentration of $5 \times 10^{18} \text{ cm}^{-3}$, and an unintentionally doped 30-nm $\text{Si}_{0.85}\text{Ge}_{0.15}$ space layer. The MQW layers have a five layers of unintentionally doped p-type ($\sim 10^{16} \text{ cm}^{-3}$) 5-nm $\text{Si}_{0.5}\text{Ge}_{0.5}$ and 25-nm Si. The collector doping is 10^{17} cm^{-3} . The commercial device is the test device made by the Taiwan Semiconductor Manufacturing Company (TSMC) using 0.35- μm BiCMOS technology with $f_T = 70 \text{ GHz}$ and $f_{\text{max}} = 55 \text{ GHz}$. The basic structure is similar to Fig. 1 without MQWs, but the details such as the doping profile and the layer thickness are not known. The 850-nm laser diode was used as a continuous light source. The HP4156A precision semiconductor parameter analyzer was used for dc measurements. The impulse response of the HPT device was measured by digital sampling oscilloscope. The electrically triggered 830-nm mode-locked Ti:Sapphire pulse laser with 50-ps full width at half maximum was used as the light source for impulse response measurement. The simulation results are compared with the experimental data of the dc and the impulse response.

III. DC PHOTOCURRENT MODELS

The complete device model is given in Fig. 2. The dark current can be essentially modeled by intrinsic model [8], [9] (Figs. 3 and 4). The error between the data and simulation is reasonably small at high current, but at low current, the agreement is not very good. In the MQW device, there is a non-ideal collector current (I_C) (ideality factor $n \neq 1$) at low current in Fig. 3 ($V_{BE} < 0.6 \text{ V}$), and the origin is not known. However, the low-current portion is not often used in the simulation. The parameter extraction method of the intrinsic model can be found in the literature [9], and no details will be addressed in this paper. Basically, the major improvement on the MEXTRAM model as compared to Gummel-Pool model includes the impact ionization model, the modeling in quasi-saturation region, the parasitic PNP transistor, and the increased accuracy of the cutoff frequency. Details are given in [8] and [9]. The dc photocurrent response of the HPT device is then described in a modified model, which includes (Section

Fig. 3. Measured and simulated Gummel plots in the dark for MQW device and regular device. The base-collector bias is 0 V.

Fig. 4. Simulated and measured common-emitter output characteristics with the constant base current. The breakdown voltage decreases as I_B increases with the nkT base combination current.

III-A) the photocurrent generation model, (Section III-B) voltage dependency model, and (Section III-C) avalanche multiplication model with the nkT base recombination current.

A. Photocurrent Generation Model

The photocurrent of the MQW device can be calculated as follows [10]:

$$B = \frac{A\eta W_{\text{op}}}{h\nu} \quad (1)$$

$$I_{BC} = qB \times f_{BC} = \frac{qA\eta W_{\text{op}}}{h\nu} (1 - \exp(-\alpha_G W_B)) \quad (2)$$

$$\begin{aligned} I_{\text{MQW}} &= qB \times (1 - f_{BC}) \times f_{\text{MQW}} \\ &= \frac{qA\eta W_{\text{op}}}{h\nu} \exp(-\alpha_G W_B) \\ &\quad \cdot [1 - \exp(-5(\alpha_S t_S + \alpha_G t_G + \alpha_S W_C))] \end{aligned} \quad (3)$$

$$\begin{aligned} I_{\text{sub}} &= qB \times (1 - f_{BC}) \times (1 - f_{\text{MQW}}) \times f_{\text{sub}} \\ &= \frac{qA\eta W_{\text{op}}}{h\nu} \exp(-\alpha_G W_B) \\ &\quad \cdot \exp(-5(\alpha_S t_S + \alpha_G t_G + \alpha_S W_C)) \\ &\quad \cdot (1 - \exp(-\alpha_S W_{CS})) \end{aligned} \quad (4)$$

where η is the apparent quantum efficiency, W_{op} is the optical power per area, A is the cross-sectional area exposed to the photons, and B is total generation rate of the photocarriers. The f is the fraction of optical absorption, and α^{-1} is the absorption depth $\sim 23 \mu\text{m}$ for Si at 850-nm wavelength. The suffixes G and S denote the depletion layer in the SiGe base region and the Si collector layer, respectively. The W_B , W_C , and W_{CS} are the thickness of the depletion layers at the SiGe base, the Si collector (the Si portion underneath MQWs) and the CS junction. The t_G , and t_S are the thickness of the SiGe layer and the Si layer in MQW layers. Due to the light doping of the MQW (10^{16} cm^{-3}), the MQWs are fully depleted. No internal reflection between the Si-Si_{0.5}Ge_{0.5} interfaces is assumed for simplicity. The optical absorption in the neutral emitter, and neutral base is neglected, but the carrier generation in the collector neutral region has to be considered for the impulse response. The dc response of these neutral regions can be incorporated effectively in the depletion region by increasing the effective depletion width. Therefore, the photocurrent can be separated by three terms in (2)–(4): optical absorption on B-C junction depletion layer, the MQW layers, and the C-S junction depletion layer. The equivalent circuit of the HPT device for optical illumination can be described by two current sources (Fig. 2). The I_{ph} describes the sum of I_{BC} and I_{MQW} , which both are generated between the base and the collector. The I_{sub} flowing from the collector to the substrate describes the photocurrent generated at the CS junction. Note that for the regular device without MQW layers (commercial TSMC device), the t_G and t_S are zero.

B. Photocurrent Voltage Dependency Model

The photocurrent of the HPT device is dependent on the width of depletion layer. The I_{ph} [(2) and (3)] is a function of W_B and W_C , and both are functions of V_{CB} . The voltage drop on the MQWs is approximately constant, and the voltage dependence of W_B and W_C follows the intrinsic model for convenience. The basic model of the depletion layer in the intrinsic model is [11], [12, pp. 31–36]

$$C_{\text{dC}} = \frac{C_{\text{jC}}}{\left(1 + \frac{V_{\text{CB}}}{V_{\text{dc}}}\right)^{p_C}} \quad (5)$$

$$W_B + W_C = \frac{\varepsilon_s}{C_{\text{dC}}} \quad (6)$$

$$W_B \approx \sqrt{\frac{N_C}{N_B}} \frac{\varepsilon_s}{C_{\text{jC}}} \left(1 + \frac{V_{\text{CB}}}{V_{\text{dc}}}\right)^{p_C} \quad (7)$$

with C_{jC} the B-C depletion capacitance at zero V_{CB} , V_{dc} the diffusion voltage, p_C the grading coefficient, and ε_s the permittivity of Si. In the intrinsic model, the C_{jC} , V_{dc} , and p_C are adjustable parameters. N_C and N_B is the doping concentration in the collector and the base region, respectively. Referring to (2) and (3), the α_S is much smaller than α_G [13], and the I_{ph} dependence on V_{CB} is dominated by I_{BC} . We can write the I_{BC} term as follows:

$$I_{\text{BC}} \approx \frac{qA\eta W_{\text{opt}}}{h\nu} \left(1 - \exp\left[-\alpha_G \left(1 + \frac{V_{\text{CB}}}{V_{\text{dc}}}\right)^{p_C} \cdot \frac{\varepsilon_s}{C_{\text{jC}}} \sqrt{\frac{N_C}{N_B}}\right]\right). \quad (8)$$

Fig. 5. Photocurrent of the regular device is simulated in the common-emitter output characteristics (in the base open mode) with measured data. It shows that the HPT can be operated at an avalanche gain region to have an extra gain.

The parameters of the intrinsic model can be extracted by the normal HBT parameter extraction procedure in the dark [9]. Then, the three parameters (C_{jC} , V_{dc} , and p_C) can be used to get the voltage dependency of the photocurrent. Note that in the MQW device, I_{MQW} is almost a constant for V_{CB} due to light doping concentration and the fully depleted MQW layers. The effect of the $\alpha_S W_C$ term in (3) is small compared to I_{BC} , due to the $\alpha_S \ll \alpha_G$ and the smaller prefactor in (3) as compared to (2).

C. Avalanche Multiplication Model

The breakdown voltage BV_{CE} dependency on the nkT base recombination current can be modeled in Fig. 4. The nkT base recombination current decrease the current gain β at the low base current (low V_{BE}). The lower current gain (β) yields a higher BV_{CE} to meet the breakdown criteria $\beta(M - 1) = 1$, where M is the multiplication factor, which increases as the reverse bias V_{CB} increases. Note that the BV_{CE} would be almost constant for the different base current if the base current were ideal 1-kT current [11]. The common-emitter characteristics of a regular device in a log I_C scale with the base open mode at different incident optical power are shown in Fig. 5. It is clear that in the avalanche gain region, the impact ionization can enhance the photocurrent. For the regular device with the nkT ($n = 2$ in this case) base recombination current, the BV_{CE} in the dark is larger than the BV_{CE} with optical illumination. Therefore, the regular HPT device can be operated at an avalanche gain region with an excess photocurrent gain, and no breakdown occurs at this V_{CE} region in the dark current. Note that this avalanche photocurrent is RC -limited. The collector resistance RC is only 53.8Ω , but it cannot be neglected at such high avalanche current.

IV. AC PHOTOCURRENT MODELS

The impulse response of HPT device has two components in the falling part [14]. The diffusion and drift of photogenerated carriers either to the emitter or to the substrate contact determine the initial portion of the fall time when the light is switched off [15]. The release of photogenerated holes at the B-E junction by the back-injected hole current to the emitters and the nkT base recombination current determines the tail portion of the impulse response (Fig. 1). In order to describe these effects in the sim-

Fig. 6. Common-emitter output characteristics for a MQW device. The HPT device was measured under the constant base current (1.45 μA) or the optical illumination of 336 μW (in the base open mode). The inset is the simulated and measured collector current as a function of collector-base bias in the emitter open mode.

ulation, some modification is added in the modified model. R1 and C1 in Fig. 2 represent the initial time constant by considering the current path of photogenerated holes to the substrate and the emitter with discharge time τ_{sub} and τ_{CB} for the substrate path and the emitter path, respectively

$$R1 \cdot C1 = \left(\frac{1-r}{\tau_{\text{CB}}} + \frac{r}{\tau_{\text{sub}}} \right)^{-1} \quad (9)$$

where

$$r = \frac{I_{\text{sub}}}{(I_{\text{ph}} - \text{induced } I_C) + I_{\text{sub}}} \approx \frac{I_{\text{sub}}}{\beta I_{\text{ph}} + I_{\text{sub}}}. \quad (10)$$

The I_{ph} -induced I_C is the amplified I_{ph} by the transistor action, and β is the current gain of the device. Therefore, β can be obtained from parameter extraction, and then r can be obtained by (2)–(4). τ_{CB} can be obtained by the impulse response of the HPT device without the substrate (S) contact (inset of Fig. 10), and τ_{sub} can be extracted by the impulse response with the substrate contact. Note that the impulse response with an open substrate contact has a very large time constant (~ 1.3 ns), and the impulse response with the substrate contact has a much higher speed. In this case, we have $\tau_{\text{CB}} = 1.3$ ns and $\tau_{\text{sub}} = 92$ ps.

R_{nkT} is used to model the time constant at the tail of the falling edge and is determined by the nkT recombination of photogenerated holes and the hole back injection current. The time constant of the nkT recombination is about $R_{\text{nkT}} \cdot (C_{\pi} + C_{\mu})$. C2 is a large capacitance to prevent R_{nkT} from affecting the dc model of the HPT device.

V. COMPARISON OF SIMULATIONS AND EXPERIMENTAL RESULTS

The common-emitter output characteristics of MQW device are shown in Fig. 6 as well as the simulation results. Referring to (2)–(4), and (10), the I_{sub} term is much smaller than I_{ph} -induced I_C in the MQW device. Therefore, we can neglect the current source I_{sub} in Fig. 2 for the MQW device, and as a result, the dc measurements have the same results in the MQW device

Fig. 7. Measured common-emitter output characteristics at the various incident optical powers in the base open mode with different base current. A different current polarity occurs at negative V_{CE} for the dark and the light exposure conditions.

for open substrate and E/S short configurations. For the photodetection, the I_C - V_{CE} output characteristics at constant optical illumination have a steeper slope than the regular I_C - V_{CE} curve. In other words, the “early voltage” is reduced in the phototransistor at the constant optical illumination (Fig. 6). To further investigate the photocurrent variation due to the V_{CE} , the HPT device is measured in the emitter open mode (the inset in Fig. 6). In this mode, the HPT device reduces to a simple PN photodiode. The measured collector/base current is the direct photocurrent without the amplification. The photocurrent varies with the V_{CB} and only can be modeled by the photocurrent voltage dependency using (8) at low voltage ($V_{\text{CB}} < 3$ V). However, when V_{CB} is too high, the avalanche multiplication occurs and makes the approximation invalid. This effect can be modeled by an empirical equation [16]

$$M = 1 + aV_{\text{CB}}^b \quad (11)$$

where M is the multiplication factor. Both a and b are constants. Fig. 6 has included (8) and (11) to obtain the simulation curves. Note that the V_{BE} can be obtained by the base current I_B , and then the V_{CB} in the inset of Fig. 6 is determined by the V_{CE} minus the V_{BE} .

Similar early voltage reduction is also observed in the regular device with the shorted E and S. The substrate contact shorted with the emitter contact enables the photocurrent I_{sub} to conduct, and the I_C has an extra component I_{sub} under light exposure (Fig. 7). To confirm this, the regular device under inverse active region (negative V_{CE}) is also measured in Fig. 7. It shows a different polarity of the I_C for the dark and light exposure conditions. The transistor under the negative V_{CE} bias has a current flow from E to C (inverse active region) in the dark and has the negative I_C . However, under the optical illumination, the photocurrent flowing from C to S makes the positive I_C . This different polarity of the I_C due to photocurrent generated at the CS junction is actually the I_{sub} term in (4). Compared to the MQW device, the I_{sub} term cannot be neglected in the regular device. Therefore, the collector current of the I_C - V_{CE} curves at zero V_{CE} is nonzero with the optical illumination (Fig. 7).

Fig. 8. Simulated and measured (a) I_{sub} and (b) I_{ph} -induced I_C of the MQW device and the regular device at the different incident optical power. The corresponding responsivities are also showed in the plots. The responsivities of both devices are 0.1–0.15 A/W for I_{sub} , and 0.8 A/W (MQW device) and 0.05 A/W (regular device) for I_{ph} -induced I_C .

Moreover, the I_C – V_{CE} output curve at the constant optical illumination of the regular device has a higher breakdown voltage as compared to the constant I_B with the same I_C in the dark. The higher breakdown voltage is also due to the I_{sub} existence, and the smaller I_{ph} than I_B is required to obtain the same I_C . Due to the nkT base recombination current, the small base current I_{ph} causes a higher breakdown voltage (smaller current gain).

The simulated and measured I_{ph} -induced I_C , i.e., amplified I_{ph} by the transistor action, I_{sub} (at $V_{CE} = 1$ V), and the responsivity at the various incident optical power are shown in Fig. 8. The MQW device and regular device have a similar I_{sub} , and the responsivity of both devices is around 0.1–0.15 A/W [Fig. 8(a)]. The responsivity is relatively independent of the optical power, which is assumed in (1). On the other hand, the responsivity of I_{ph} -induced I_C in the MQW and the regular devices are 0.8 and 0.05 A/W, respectively [Fig. 8(b)]. The I_{ph} -induced I_C is relatively large in the MQW device due to large I_{MQW} term. Therefore, in the MQW devices, the I_{sub} can be neglected, similar to the previous HPT device simulation [6], [7]. However, in the regular devices, there is no I_{MQW} term in (2)–(4), which makes the I_{ph} -induced I_C small and the I_{sub} cannot be neglected. Therefore, the current source I_{sub} should be added in Fig. 2.

Finally, the dc characteristics of the HPT for both the MQW and the regular devices are obtained by the three models

Fig. 9. Common-emitter output characteristics at different incident optical power in the base open mode for (a) the regular device and (b) the MQW device.

(photocurrent generation model, voltage dependency model, and avalanche multiplication model), and two current sources (I_{ph} and I_{sub}). The common-emitter output characteristics at various incident optical powers in the base open mode for both the MQW and the regular device are shown in the Fig. 9. The simulation curves for the regular devices [Fig. 9(a)] and the MQW devices [Fig. 9(b)] are very close to the measurement data, indicating the accurate modeling for the dc characteristics.

The simulated and measured impulse responses of the regular HPT device with shorted E/S are shown in Fig. 10. The responsivity and discharge times are also listed in Table I. The initial fall time is due to the drift and diffusion of photogenerated holes from the Si collector. The tail of the impulse response is determined by the nkT recombination and back injection hole current [17]. The inset is the wider impulse response when the substrate contact is open (time constant ~ 1.3 ns). When the emitter and the substrate are shorted, the substrate contact provides the current path of photogenerated holes to the substrate and ground (emitter) (Fig. 1). As the result, the substrate contact shorted to the emitter is a key to increase the speed of the HPT device [15], [18]. Therefore, the factor r in (9) and (10) is to describe the substrate contact behavior. The impulse response (inset of Fig. 10) with an open substrate can be modeled by setting $r = 0$ in (9) and (10). The simulation curve of the impulse response with E/S short is also shown in Fig. 10, and there is a good agreement between the measurement and the simulation.

Fig. 10. Impulse response of a regular device. The initial fall time is due to the drift and diffusion of photogenerated holes in the collector. The tail is due to the nkT recombination and back injection hole current. The inset is the wider impulse response when the substrate contact is open.

TABLE
DISCHARGE TIMES AND THE RESPONSIVITY OF BOTH THE MQW DEVICE
AND REGULAR DEVICE

	Discharge time		Responsivity	
	τ_{CB}	τ_{sub}	I_{ph} -induced I_C	I_{sub}
MQW device	948ps	109ps	0.8 A/W	0.1~0.15 A/W
Regular device	1.3ns	92ps	0.05 A/W	

VI. CONCLUSION

In conclusion, the comprehensive study of Si-SiGe HPTs using the equivalent circuit modeling is investigated. A modified MEXTRAM model is used to model the HPT. The effects of voltage dependent on the width of depletion layer and the impact ionization are included to determine the photocurrent. The "early voltage reduction" under the constant illumination and an extra gain of the optoelectronic conversion at avalanche gain region are also incorporated in the modified model. For ac response, the HPT speed can be enhanced by the nkT recombination current and the substrate contact shorted to the emitter. Good agreement between measurement and simulation is demonstrated.

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Feng Yuan (S'01) received the B.S. degree in electrical engineering from National Taiwan University (NTU), Taipei, Taiwan, R.O.C. in 2001. He is currently pursuing the Ph.D. degree at the Department of Electrical Engineering, Graduate Institute of Electronics Engineering, NTU.

His research interests include SiGe HPT modeling and circuit design for optical communication.

Jin-Wei Shi was born in Kaohsiung, Taiwan, R.O.C., on January 22, 1976. He received the B.S. degree in electrical engineering from National Taiwan University, Taipei, Taiwan, in 1998 and the Ph.D. degree from the Institute of Electro-Optical Engineering, National Taiwan University, Taipei, in 2002.

He was a Visiting Scholar at the University of California, Santa Barbara, from 2000 to 2001. From 2002 to 2003, he served as a Post-Doctoral Researcher at the Electronic Research and Service Organization, Industrial Technology Research Institute. He is an Assistant Professor at Department of Electrical Engineering, National Central University, Taoyuan, Taiwan. His current research interests include ultrahigh-speed/power optoelectronic devices, such as photodetectors, electro-absorption modulators, sub-millimeter wave photonic transmitters, and semiconductor lasers. He demonstrated a novel traveling-wave photodetector with record high electrical bandwidth-peak output power product performance. Dr. Shi was the invited speaker at the 2002 IEEE LEOS.

Zingway Pei received the B.Sc. degree in physics from the National Cheng-Kung University, Tainan, Taiwan, R.O.C., in 1994 and the M.Sc. degree in electrical engineering from the National Tsing Hua University, Hsinchu, Taiwan, in 1996. He is currently pursuing the Ph.D. degree in the Department of Electrical Engineering, National Tsing Hua University.

He joined the Electronic Research and Service Organization (ERSO), Hsinchu, Taiwan, in April 2000. His research interests include formation and applications of Si Nanodots, SiGe phototransistors, and Si-Ge quantum devices.

Chee Wee Liu (M'99-SM'00) received the B.S. and M.S. degrees in electrical engineering from National Taiwan University (NTU), Taipei, Taiwan, R.O.C., in 1985 and 1987, respectively, and the Ph.D. degree in electrical engineering from Princeton University, Princeton, NJ, in 1994.

He is a Professor at NTU. His current research interests include CMOS optoelectronics, high-speed SiGe devices, and strained-Si/high- κ /metal gate. He invented the first MOS tunneling light-emitting diode and photodetector and has two U.S. patents.