# Impact of Passivation and Reliability for Base-exposed InGaP/GaAs HBTs

Jae-Woo Park[a]

*Department of Electrical Engineering and Computer Science, KAIST,*
*373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea*

[a]E-mail : hbtpark@ee.kaist.ac.kr

Reliability between passivated and unpassivated process with the base-exposed InGaP/GaAs HBTs was studied. A passivation of HBT was attempted by $SiO_2$ thin film deposition at 300 °C by means of PECVD. Base-exposed InGaP/GaAs HBTs before and after passivation were investigated and compared in terms of DC and RF performance. Over a total period of 30 days, passivated HBTs show only 2 % degradation of DC current gain for the high current density of 40 KA/cm$^2$. The measured thermal resistance of 2 x 30 μm$^2$ single emitter InGaP/GaAs HBT passivated with PECVD $SiO_2$ devices can be extracted and was founded to be 1430 K/W. The estimated MTTF was 2 x 10$^7$ hr at $T_j$ = 125 °C with an activation energy ($E_a$) of 1.37 eV.

## 1. INTRODUCTION

Nowadays, InGaP HBTs are world-widely being used for various applications such as power amplifiers, VCOs and Front end modules etc[1-5]. Also, InGaP has been recognized as long life material comparing to AlGaAs materials. However, Reliability of InGaP HBTs is still an important issue to extend the lifetime of the device as possible. An important step in the HBT process is the passivation of the device. A good passivation layer plays a role of preventing degradation of the device and reducing the density of surface states and results in low surface leakage current. This leads to long-lifetime device characteristics as necessary in practical applications.

Native oxide grown on Si, silicon dioxide ($SiO_2$), is an excellent passivation layer, as well as a perfect insulator in Si based semiconductors. However, passivation of compound semiconductors is difficult because it involves treatment of a semiconductor surface which in case of III-V compounds is known to suffer from increased surface states and Fermi level pinning.

Many attempts for deposition of native $SiO_2$ and SiO oxide layer on GaAs and other III-V compound semiconductors have been made but the results obtained were not satisfactory. For instance, in the case of GaAs, since the native oxide on GaAs consists of a mixture of unstable, non-uniform elements such as $Ga_2O_3$, $As_2O_5$,

Ga0 etc., this layer can not be reliable for insulation or passivation purposes[6]. Thus, a good "extrinsic" passivation layer on GaAs and related compound semiconductors is required for long-lifetime devices as necessary for wireless and optical communication systems. There are many types of passivation materials such as $SiO_2$, SiO, $Si_3N_4$, $SiN_x$, and Polyimide that can be used and the choice among them is not straight forward[7]. Various deposition techniques, i.e. PECVD, e-beam evaporation, spin coating are available for depositing the passivating layers. As to date, no universal passivation technique is available. In practice, the type of passivation material is insensitive and does not play as an important role as the process technique in obtaining a good passivation properties[8]. If the emitter mesa of the HBT is fully surrounded by the base contact, the base surface recombination current may be assumed to be constant along the emitter periphery. The dependence of current gain on P/A ratio can then be evaluated as follows;

$$\frac{1}{\beta} = \frac{1}{\beta i} + \frac{J_{surf} P}{J_C A}$$

(1)

where β and β$_i$ are the measured and the ideal current gain without any surface recombination current, respectively. P and A are the emitter periphery and area,

$J_{surf}$ is the surface recombination current per centimeter and $J_C$ is the collector current density. Thus, the exposed base region ratio comparing to the emitter area is an important parameter to decide the surface leakage current.

In this study, passivation of HBT was attempted by $SiO_2$ (4500 Å) thin film deposition at 300 °C by means of Plasma Enhanced Chemical Vapor Deposition (PECVD). The base-exposed InGaP/GaAs HBTs before and after passivation were investigated and compared in terms of DC and microwave performance.

## 2. CHARACTERIZATION OF PASSIVATION FOR BSAE-EXPOSED INGAP/GAAS HBT

PECVD $SiO_2$ was deposited after HBT fabrication including airbridges was completed. Fig. 1 shows the cross sectioned SEM view of passivated base-exposed InGaP/GaAs HBT. Since PECVD passivation was carried out in the last step of the HBT process, it was necessary to investigate whether the emitter-base side wall and the exposed base layer are fully covered by $SiO_2$. As shown in these figures, the exposed base surface layer where the major surface recombination current flows is successfully covered by the $SiO_2$ passivation layer, the devices compared were 2 x 10 $\mu m^2$ single emitter and 2 finger 5x10 $\mu m^2$ emitter HBTs.

After passivation, the DC gain is decreased slightly but no obvious change in Gummel plots was observed. The base current was founded to increase slightly after passivation. To explain the observed trend, we need to consider the base current components which include: (1) the space-charge recombination current ($I_{B,scr}$) in the base-emitter junction, (2) the bulk recombination current ($I_{B,bulk}$) in the base region, (3) the current ($I_{B,p}$) arising from holes being back injected across the forward biased base-emitter junction from the base into the emitter, (4) the surface recombination current ($I_{B,surf}$) at the exposed
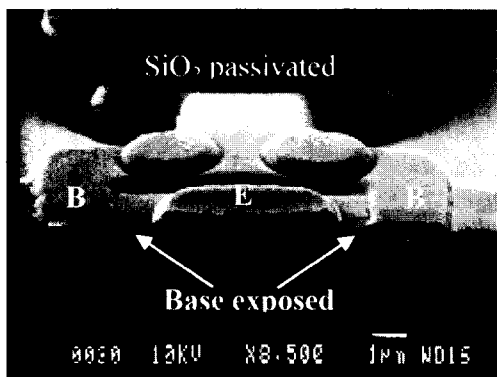


Fig. 1. SEM pictures for the cross section of passivated InGaP/GaAs HBTs with PECVD $SiO_2$.
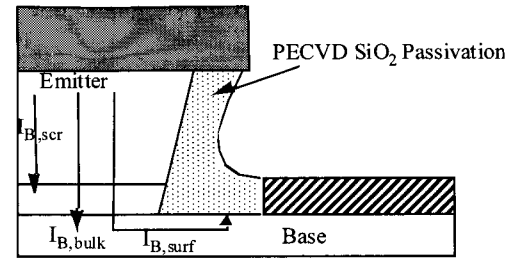


Fig. 2. The schematic diagram of the four major base currents in HBTs.
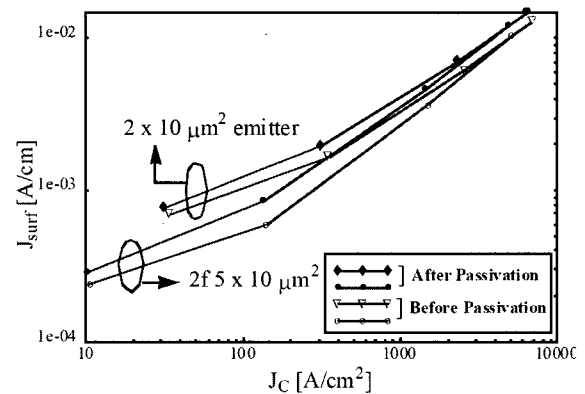


Fig. 3. The surface recombination current as function of the collector current density before and after passivation.

emitter periphery and exposed base region[9,10]. A schematic diagram depicting these four major base currents in HBTs is shown in Fig. 2. The surface recombination current $J_{surf}$ can be evaluated as a function of the collector current density by evaluating the HBT current gain before and after passivation. Use of Eq. (1) allows then evaluation of $J_{surf}$. This is plotted in Fig. 3 for two different types of geometry. The surface recombination current after passivation with PECVD $SiO_2$ was slightly increased for both 2 x10 $\mu m^2$ emitter and 2 finger 5 x 10 $\mu m^2$ emitter HBTs. Moreover, the surface recombination current for 2 x 10 $\mu m^2$ emitter HBT is higher than that of 2 finger 5 x10 $\mu m^2$ emitter devices since the former has a larger P/A (Perimeter/ Area) ratio; P/A was 12000 $cm^{-1}$ for 2 x10 $\mu m^2$ emitter HBT and 6000 $cm^{-1}$ for 2 finger 5 x10 $\mu m^2$ emitter devices. This is consistent with the expectation of higher surface recombination current through a larger emitter mesa periphery. The increase of the base current after passivation is mainly due to additional base surface recombination at the emitter mesa periphery interface with the $SiO_2$ passivation film. Surface states in the passivated surface provide additional generation-recombination centers and leads in formation of an electron accumulation layer, which acts as a surface leakage path. Similar surface recombination trends were reported by other using various dielectric films[11].
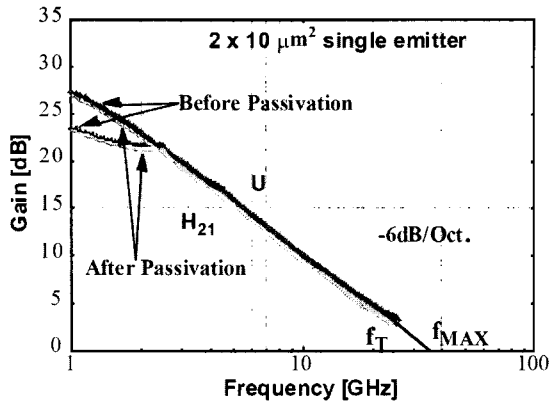
Fig. 4. Microwave performance of the 2 x10 μm² emitter HBT before and after passivation with PECVD SiO₂.

Figure 4 illustrates a comparison of microwave performance before and after passivation for a 2 x10 μm² emitter HBT. The microwave performance is almost the same before and after passivation except in the low frequency region (around 1 GHz) which is dictated primarily by DC gain characteristics. We conclude that the PECVD SiO₂ passivation layer tested in this work does not affect the microwave performance and can be a potential candidate for HBTs with good reliability characteristics. The reliability characteristics of these passivated devices were evaluated and are discussed in the next section.

## 3. RELIABILITY TEST OF HBTS

A program which controls the base current ($I_B$) to maintain constant collector current density ($J_C$) was developed using LabView control software. The collector current density ($J_C$) values selected for the tests were 25 and 40 kA/cm². A bias tee was connected at the collector and emitter terminals to suppress device oscillation. I-V characteristics were measured and compared before and after reliability tests. Passivated devices were prepared with PECVD SiO₂ ($t_{ox}$= 4500 Å) as mentioned in the previous section.

### 3.1 Reliability tests of unpassivated InGaP/GaAs HBTs

The reliability of unpassivated 2 x 30 μm² single emitter devices with $f_T$ = 58 GHz, $f_{max}$ = 100 GHz was investigated and tests were performed as a function of current density. The device shown in Fig. 5(a) was tested at 25 kA/cm². Its current gain was monitored over 9 days and was found to decrease by not more than 10 %. As the current density increases, the HBT is subjected to more stress and is therefore expected to degrade more rapidly. This is shown in Fig. 5(b) which corresponds to
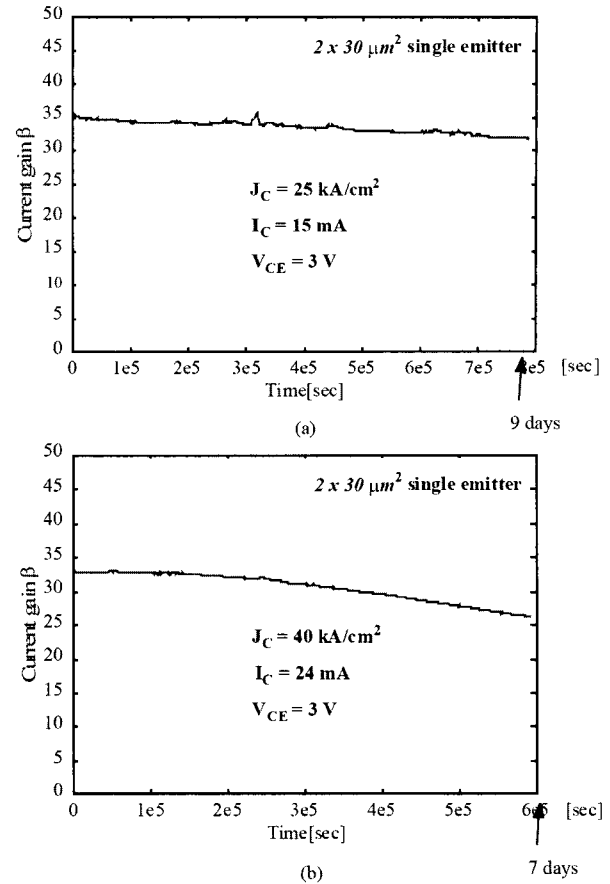


Fig. 5. Reliability tests of unpassivated 2 x 30 μm² InGaP/GaAs HBTs.

40 kA/cm² bias stress of another device of comparable microwave performance. The tests were performed in this case over a period of 7 days. During the first 2 days, the device was found to remain stable, Its gain decreased after this initial period by 21 % within 7 days. Possible reason for the observed DC gain degradation are surface reaction with O₂ ambient through exposed surface of the device in high collector current conditions and degradation in E-B heterojunction interface quality. Considering the fact that stress at 25 kA/cm² is generally acceptable for testing HBT reliability, we consider that these unpassivated devices show modest degradation.

### 3.2 Reliability tests of passivated InGaP/GaAs HBT

Passivated 2 finger 5 x 10 μm² emitter InGaP HBTs with a 4500 Å SiO₂ layer were also subjected to reliability tests. A PECVD deposited SiO₂ layer was used for passivation. These tests led to very encouraging results, as discussed next. Fig. 6 shows such reliability tests for passivated 2 finger 5 x 10 μm² emitter HBTs operated a current density ($J_C$) of 40 kA/cm². The results show that over a total period of 30.5 days, passivated HBTs
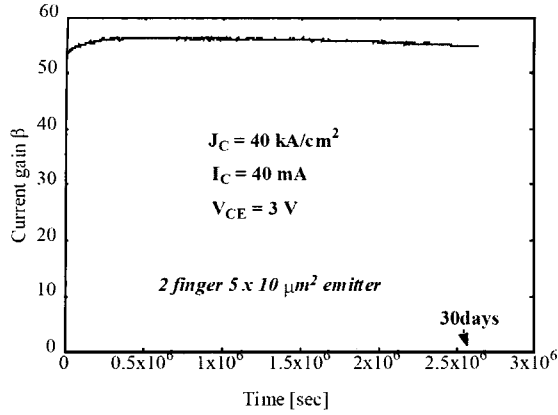
Fig. 6. Reliability tests for passivated 2 finger 5 x 10 $\mu m^2$ emitter HBTs operated a current density of 40 kA/cm$^2$.
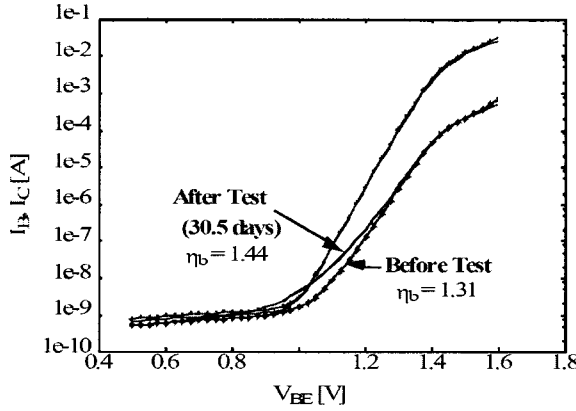


Fig. 7. Gummel plot of the passivated InGaP/GaAs HBTs before and after the reliability stress tests.

show only 2 % degradation of DC current gain despite the fact that they are subjected to the high current density of 40 kA/cm$^2$ used for these tests. Passivated HBTs show a much more stable performance than unpassivated ones.

Shown in Fig. 7 is the Gummel plot of the passivated InGaP/GaAs HBTs before and after the reliability stress test. The results show that the current gain at medium to high collector current is not very much affected by the stress. In the low collector current region ($I_C < 10^{-6}$ A), however, the base ideality factor ($\eta_B$) is increased from 1.31 to 1.44.

This indicates that the space-charge recombination current ($I_{B,scr}$) is increased and then activation of recombination centers in the base-emitter junction takes place during the long reliability stress test.

### 3.3 Evaluation of mean-time-to-failure (MTTF) for the passivated InGaP/GaAs HBTs

The Mean-Time-To-Failure (MTTF) of a device can

be extracted under various junction temperatures and is expressed by the Arrhenius equation:

$$MTTF = Kexp(E_a/kT) \qquad (2)$$

where K is a constant, $E_a$ is the activation energy of the degradation mechanism (eV), k is Boltzman constant (k = 8.617 x 10$^{-5}$ eV/K) and, T is absolute temperature in Kelvin. The activation energy ($E_a$) can be derived using Eq. (2) as applied to two reliability experiments with corresponding MTTF$_1$ and MTTF$_2$ at junction T$_1$ and T$_2$. The junction temperature and the thermal resistance of the device are also calculated when performing these studies.

The junction temperature of the device can be expressed as follows,

$$T_j = T_{ambient} + \Delta T \qquad (3)$$

where $\Delta T = P_{diss}$ x R$_{th}$, P$_{diss}$ is the dissipated power and R$_{th}$ is the thermal resistance of the device. The calculation of the thermal resistance (R$_{th}$) can be achieved by performing the following test and analysis [12]: (1) the base-emitter voltage (V$_{BE}$) is measured at different substrate temperatures (T) and collector current levels; (2) the relation between V$_{BE}$ and the dissipated power (P$_{diss}$) is determined by measurement of V$_{BE}$ at a constant collector current level and substrate temperature at various V$_{CE}$. (3) By combining the two plots of V$_{BE}$ vs. P$_{diss}$ and V$_{BE}$ vs. Temp. a plot of the calibrated temperature (T) vs. the dissipated power (P$_{diss}$) can be drawn and R$_{th}$ can be extracted from this combined plot as shown in Fig. 8. The measured devices were in this case 2 x 30 $\mu m^2$ single emitter InGaP/GaAs HBT passivated with PECVD SiO$_2$ as discussed in the previous section. The thermal resistance of the device can be extracted from the slope of Fig. 8 and was founded to be 1430 K/W.

High temperature life time tests allowed MTTF evaluation. Fig. 9 shows the dependence of the Mean-Time-To-Failure (MTTF) to the junction temperature (T$_j$). The failure criterion used in this work was a 20 % current gain reduction from the initial current gain value before stress application. Each of the three data points in this figure corresponds to different ambient temperature and represents the MTTF of the device which was a 2 x 30 $\mu m^2$ single emitter InGaP/GaAs HBTs subjected to V$_{CE}$ = 3.0 V, J$_C$= 33.3 kA/cm$^2$ bias stress.

The estimated MTTF was 2 x 10$^7$ hr at T$_j$ = 125 °C with an activation energy (E$_a$) of 1.37 eV. This compares well with reported activation energy values for InGaP/GaAs HBTs which are founded to be in the range of 0.7 to 2.0 eV[13,14] : the MTFF versus temperature dependence of HBT, reported by other groups is also shown in this figure. The activation energy is known to
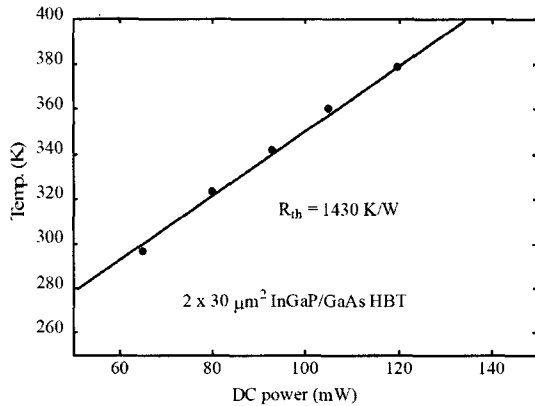
Fig. 8. The extracted thermal resistance ($R_{th}$) using the calibrated temperature as function of DC dissipated power for 2 x 30 $\mu m^2$ InGaP/GaAs HBTs.
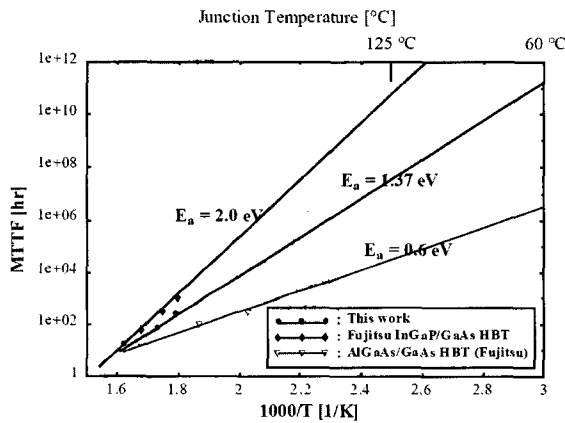


Fig. 9. Arrhenius plot of MTTF for devices subjected to variuos ambient temperature.

vary depending on the bias stress condition, layer structure and base refractory metal[14]. The results of passivated InGaP/GaAs HBTs tested in this work suggest satisfactory performance and possibility of application of the developed technology in applications such as wireless and optical communication systems.

## 4. CONCLUSION

In this work, the base-exposed InGaP/GaAs HBTs before and after passivation were investigated and compared in terms of DC and microwave performance. Passivated HBT devices were obtained by $SiO_2$ (4500 Å) thin film deposition at 300 °C using PECVD. The surface recombination current after passivation with PECVD $SiO_2$ was slightly increased for both 2 x10 $\mu m^2$ emitter and 2 finger 5 x 10 $\mu m^2$ emitter HBTs. The increase of

the base current observed after HBT passivation results from additional base surface recombination at the emitter mesa periphery. The reliability characteristics of passivated and unpassivated InGaP/GaAs HBT devices were also investigated to evaluate the device life-time. The reliability of unpassivated 2 x 30 $\mu m^2$ single emitter devices was investigated, at a collector current density ($J_C$) of 25 kA/cm$^2$. The current gain was monitored over 9 days and was found to decrease by not more than 10 %. Reliability tests were also carried out 2 finger 5 x 10 $\mu m^2$ emitter InGaP HBTs with a 4500 Å PECVD $SiO_2$ passivation layer. The stress test was performed for 30.5 days and the HBT continued to operate with only 2 % of current gain degradation despite the rather high current density (40 kA/cm$^2$) used for these tests. Gummel plots of the passivated InGaP/GaAs HBTs before and after stress test show that the current gain at medium to high collector current is not much affected by the stress but the base ideality factor ($\eta_B$) is increased from 1.31 to 1.44 in the low collector current region ($I_C < 10^{-6}$ A). This suggests that the space-charge recombination current ($I_{B,scr}$) is increased due to the activation of recombination centers in the base-emitter junction.

The dependence of the Mean-Time-To-Failure (MTTF) on the junction temperature ($T_j$) was also investigated and the estimated MTTF in this work was 2 x $10^7$ hr at $T_j$ = 125 °C with an activation energy ($E_a$) of 1.37 eV.

## ACKNOWLEDGMENT

## REFERENCES

[1] J. Kim, S. Ko, S. Jeon, J.-W. Park, and S. Hong, "Balanced topology to cancel Tx leakage in CW radar", IEEE Microwave and Wireless Components Letters, Vol. 14, No. 9, p. 443, 2004.

[2] J. Kim, D. Baek, S. Jeon, J.-W. Park, and S. Hong, "A K-band InGaP/GaAs HBT balanced MMIC VCO", IEEE Microwave and Wireless Components Letters, Vol. 13, No. 11, p. 478, 2003.

[3] K. A. Lee, D. H. Lee, H. Park, S. Cheon, J.-W. Park, H. Yoo, and S. Hong, "A InGaP/GaAs HBT WLAN power amplifier with power detector", 34" European Microwave Conference, p. 345, 2004.

[4] O. Lee, J. Kim, S. Jeon, J.-W. Park, and S. Hong, "A V-band VCO and Frequency Divider MMICs for Phase-locked Loop", IEEE MTT-S Digest, p. 1321, 2004.

[5] S. S. Choi, J. Y. Lee, H. K. Choi, J. C. Lee, B. Lee,

J. H. Kim, N. Y. Kim, Y. H. Lee, S. H. Jeon, and J. W. Park, "High linear, low power and broad-bandwidth double balance mixer with low LO-power using InGaP/GaAs HBT MMIC process", Asia-Pacific Microwave Conference, Vol. 2, p. 886, 2003.

[6] J.-W. Park, Master thesis, Kwangwoon University, Seoul, Korea, 1989.

[7] D. Caffin, L. Bricard, J. L. Courant, L. S. How Kee Chun, B. Lescaut, A. M. Duchenois, M. Meghelli, J. L. Benchimol, and P. Launay, "Passivation of INP-based HBT's for high bit rate circuit applications", Proc. of the 1997 Int. Conf. on Indium Phosphide and Related Materials. Cape Cod, MA, USA., p. 637, 1997.

[8] J. J. Liou, C. I. Huang, B. Bayraktaroglu, and K. B. Parab, "Base and collector leakage currents of AlGaAs/GaAs HBTs", J. Appl. Phys., Vol. 76, No. 5, p. 3187, 1994.

[9] W. Liu, "Handbook of III-V Heterojunction Bipolar Transistors", Wiley-Interscience, p. 143, 1998.

[10] S. M. Sze, "High-Speed Semiconductor Devices", Wiley-Interscience, p. 337, 1990.

[11] T. Kikawa, S. Takatami, H. Masuda, and T. Tanoue, "Passivation of InP-based HBTs-relation to surface fermi-level", Proc. of the 1998 Int. Conf. On Indium Phosphide and Related Materials., Tsukuba, Japan, p. 76, 1998.

[12] A Samelis, Ph. D thesis, University of Michigan, 1996.

[13] T. Takahashi, S. Sasa, A. Kawano, T. Iwai, and T, Fujii, "High-reliability InGaP/GaAs HBTs fabricated by self-aligned process", Proceedings of the 1994 IEEE International Electron Devices Meeting, San Francisco, CA, USA, p. 191, 1994.

[14] S. R. Bahl, L. H. Camnitz, D. Houng, M. Mierzwinski, J. Turner, and D. Lefforge, "Reliability investigation of InGaP/GaAs HBTs", Proceedings of the 1995 International Electron Devices Meeting Washington, DC, USA, p. 815, 1995.