Low noise amplifiers in SiGe hetero-junction bipolar process using reduced pressure chemical vapor deposition

Bongki Mheen[1,2], Chan Woo Park, Sang Hoon Kim, Jin-Yeong Kang, Songcheol Hong[2]

[1]Basic Research Laboratory, Electronics and Telecommunications Research Institute,
161 Gajeong-Dong, Yuseong-Gu, Deajon, Republic of Korea
Tel: +82-42-860-6217, Fax: +82-42-860-6183, Email: mheen@ieee.org
[2]Dept. of EECS, Korea Advanced Institute Science and Technology, Deajon, Republic of Korea

Abstract — **In this paper, an economic SiGe HBT (hetero-junction bipolar transistor) process using reduced pressure chemical vapor deposition (RPCVD) process of high throughput and the cheap localized oxidation of silicon (LOCOS) instead of shallow trench, was developed and characterized. To test its feasibility, several low noise amplifiers were designed and fabricated. As well as high cutoff frequency and low noise SiGe HBT devices, the passive elements including planar spiral inductors with only two metal layers, metal-insulator-metal capacitor, three kinds of resistors, and varactor diode were also integrated in the process. With carefully designing of the base profile and adopting finger-type structure, the measured minimum noise figure of 1.5 dB and associated gain of 16 dB at 1.8 GHz consuming the collector current of 4.6 mA at the supply voltage of 2.5V, were obtained in the low noise device. After on-wafer calibration, one of the fabricated low noise amplifiers was measured as 2.5 dB NF and 21 dB insertion gain at the frequency of 1.8 GHz with the supply voltage of 2.5 V. Those results using the epitaxial growth by RPCVD are firstly reported, and show its possibility to RF arena.**

I. Introduction

The success of silicon devices in the ever-expanding RF market is the result of searching more reliable and chipper process to achieve comparable performance as well as enhancing the RF circuit design itself. For the selection of the appropriate process at the RF application there are many factors to be considered: 1) low noise with high gain at low current consumption, 2) high linearity without compromising, and 3) low cost for fabrication, the first two of which are crucial to the receiver design relieving from various problems at the front-end and base-band design, and the last of which is the result of overwhelming growth of wireless electronics market.

As one success of silicon device, RF CMOS process is used at lots of RF applications, for an example, Bluetooth® RF front-end and single-chip products [1] [2], which mainly resulted from the merit of low cost by silicon substrate and economic process technique. The performance of RF CMOS device, however, is partially limited, especially when compared to its counter part, bipolar device. Even though the scaling of CMOS gives a room to solve the problem, the limitation comes from the trans-conductance of CMOS, which is proportional to the square root of bias current, while bipolar device directly proportional to bipolar bias current. Consequently, low power consumption in RF CMOS relies mainly on the device scaling, because the gain of RF CMOS could not be increased sufficiently even under large bias current, which is not allowed in most situations requiring low power consumption.

Meanwhile, the breakthrough of low gain and high noise in standard silicon bipolar silicon which is a major obstacle due to high intrinsic base resistance, was achieved by introducing SiGe epitaxial layer onto the base region of bipolar transistor [3], and the cutoff frequency of recent SiGe bipolar was recently reported over 200 GHz [4], up to 350 GHz [5].

In this paper, we developed low cost and high performance SiGe HBT process using reduced pressure chemical vapor deposition (RPCVD). Passive elements such like spiral planar inductor, metal-insulator-metal (MIM) capacitor, three types of resistors, and varactor diode were all integrated in the process. Our purpose of this paper is to evaluate this SiGe HBT process using RPCVD without introducing expensive process technologies and to implement several of low noise amplifiers for the feasibility test to RF applications.

II. Device Fabrication

The standard SiGe HBT is shown in Fig. 1. A junction and LOCOS isolation were used to isolate devices and device terminals respectively. The thickness of collector was 8000 Å on the thick and highly doped sub-collector. The base epitaxial layer was grown by RPCVD. Standard base profile was shown in Fig. 2. In the standard base profile the total Ge thickness was 400 Å with the rectangular layer of Boron (150 Å). The base growth was followed by Ti-silicidation (C54-TiSi2) that is critical to the extrinsic base resistance between the base terminal and the intrinsic base-emitter junction. The C54-TiSi2 was obtained by rapid thermal anneal at 850 ºC for 30 second with no harm to the base profile.

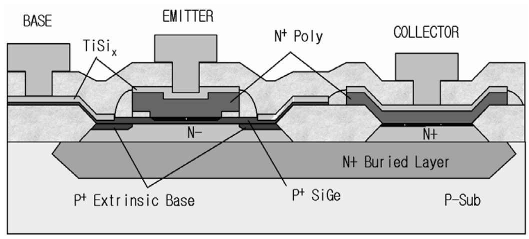

Fig. 1. Schematic of the SiGe HBT fabricated.

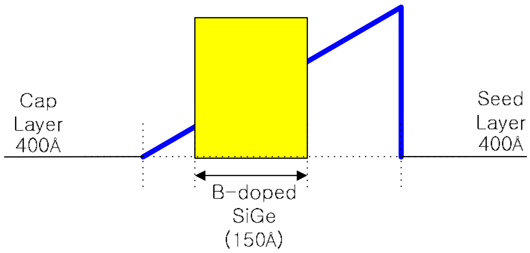

Fig. 2. The standard base profile used.

The high frequency properties of active devices are determined in very complicated ways. We tried to get sufficient low extrinsic base resistance by controlling the thickness of base and Ti-silicidation condition, and to reduce the extrinsic base-collector capacitance by changing the condition of extrinsic base implant condition, i.e., the junction depth and the depletion width of the extrinsic base-collector junction. All these parasitic elements can be extracted by several methods to check the variation by process changes [6] [7].

Passive elements such like spiral on-chip inductor, MIM capacitor, three types of resistors, and varactor diode were also implemented. Especially the on-chip varactor diode is important in the process because the flicker noise of SiGe HBT is quite lower than other techniques [8], enabling design and implementation of the voltage-controlled oscillator with lower phase noise. In our process, without any additional mask layer and process change, we achieves high Q factor varactor by only changing mask [9], which is not dealt in this paper. Inductor layout was also designed to achieve high Q factor to use low noise and high Q application such like in low noise amplifier.

We measured and analyzed the HBT's having the emitter size of 0.5×6.0 μm^2 and ten fingers of 1×6 μm^2 in the standard SiGe HBT process. For the implementation test, several low noise amplifiers were designed and fabricated. The characteristics of a fabricated low noise amplifier for 1.8 GHz, including the noise figure and insertion gain, were presented.

II. Results

A. DC and AC characteristics

Using Agilent parameter analyzer 4156B and Cascade probe station DC characteristics were measured on wafer. Gummel plots of single finger and 10-finger device are shown in Fig. 3(a) and Fig. 3(b), respectively. The current gains were nearly flat over a wide range of collector current. Collector-emitter breakdown voltages of both devices were about 4.5V. Early voltages of all devices were over 50 V enabling high output impedance and good small signal performance.

Using Agilent DC modular source 4142B and network analyzer 8510C the scattering parameters were measured. De-embedding procedure followed scattering parameter measurement to eliminate the pad and ground line parasitic elements [10]. From the de-embedded result the cutoff frequency and maximum oscillation frequency of SiGe HBT having the emitter size of 0.5x6.0 μm^2 were measured as about 45 and 35 GHz, respectively.

B. Noise characteristics

Noise parameters were measured using Agilent 8970B noise figure measurement system with the ATN NP5 automatic tuner which changes input impedance of the device under test, enabling faster measurement than a mechanical tuner. But this measurement includes calibration process that may affect a detrimental effect on the measured results. Even though the several methods are provided to alleviate these problems including fitting algorithms, reliable results can be gained by repeated measurements and result inspections.

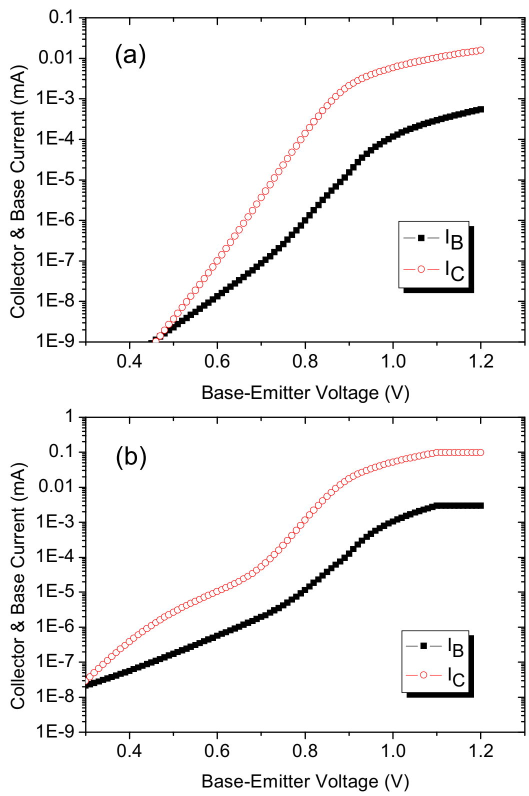

Fig. 3. Gummel plot of a) 0.5x6.0 μm^2 single-finger HBT and b) 10-finger of 1.0x6.0μm^2 multi-finger HBT.

With the optimized base profile design, extrinsic base resistance control, and the carefully designed multi-finger device layout, the measured minimum noise figure of 1.5 dB were obtained in the low noise device consuming the collector current of 4.6 mA, which is quite lower power consumption compared with the result of general CMOS process. The associated gains, the maximum available gains with the source matched to the noise minimum points, were 16 dB at 1.8 GHz and 9 dB at 5.8 GHz even at the low current consumption. The minimum noise figure and the associated gain of the 10-finger device are shown in detail at Fig. 4.

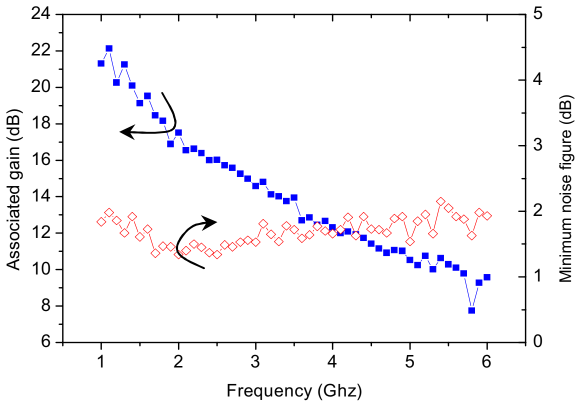

Fig. 4. Measured noise performances with the bias current of 4.6mA and a supply voltage of 2.5V.

B. Low noise amplifier

A simple schematic of the fabricated low noise amplifier is shown in Fig. 5. It consists of two-stage amplifiers. The first stage has an emitter degeneration inductor for noise and input matching, and a load inductor to reduce the noise figure. Photograph and characteristics of 1.8 GHz low noise amplifier among the several fabricated ones were shown Fig. 6 and Fig. 7, respectively. The low noise amplifier was designed to have a peak gain at 1.8 GHz including all matching networks. The insertion gain of the low noise amplifier was measured 21 dB with current consumption of only 3 mA with a supply voltage of 3.0V. Such low power consumption is resulted from the optimized base profile design. The input and output return losses were measured as -5.0 dB and -10.9 dB, respectively. The performance parameters of the fabricated low noise amplifier are summarized in Table 1.

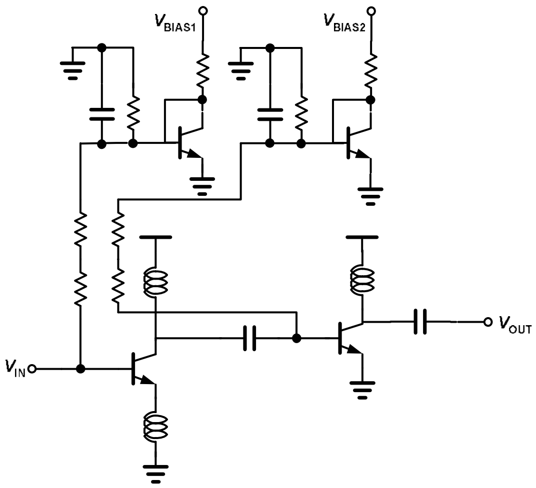

Fig. 5. Noise performance with the bias current of 4.6mA with a supply voltage of 2.5V.

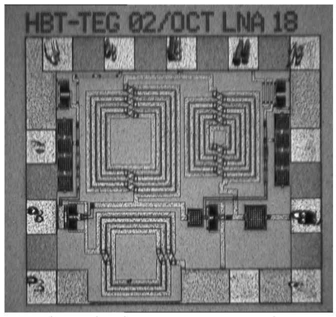

Fig. 6. photograph of the 1.8 GHz low noise amplifier fabricated.

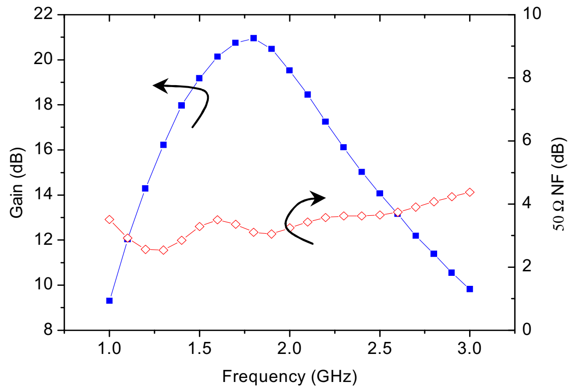

Fig. 7. Measured gain and noise properties of 1.8 GHz low noise amplifier fabricated.

Table 1. Performance parameters for the fabricated low noise amplifier.

Parameters	Units	Values
Frequency	GHz	1.8
Insertion gain	dB	21.0
Noise figure	dB	2.5
Input Return loss	dB	−5.0
Output return loss	dB	−10.9
Supply voltage	V	2.5
Consumption current	mA	3

IV. Discussion

In our early development non-self aligned SiGe HBT by RPCVD had been tried [11] in which the extrinsic base resistance and series emitter resistance can be reduced, enhancing high frequency performance. But this type of structure decreases the yield of device and also increase the fabrication cost. Thus the self-aligned structure was used in this paper. In some advanced processes chemical-mechanical polishing (CMP) and shallow trench are used, which can reduce these parasitic elements effectively to increase device performance [4] [5]. But these processes need additional fabrication cost to adopt. Since the widely prevailed technology has economic merits, we used the traditional LOCOS process in spite of suffering RF performance limitation.

When designing the structure of active device, the input section of the bipolar is very important to get better high frequency properties. For example, the extrinsic base resistance is one of key parameters to determine the maximum oscillation frequency and noise property. In the current self-aligned structure the extrinsic base sheet resistance is controlled under 15Ω/□. Another important parameter that controls the gain at high frequency is extrinsic and intrinsic base-collector capacitance. The product of extrinsic base resistance and the base-collector capacitance is easily derived from the relationship between the cutoff frequency and the maximum frequency like in Eq. 1. This equation is simple and good measure for expecting the high frequency properties, because the cutoff frequency and maximum oscillation frequency is extracted directly by simple measurement.

$$R_{BB} \cdot C_{BC} \cong \frac{f_T}{8\pi \cdot f_{\max}{}^2} \qquad (1)$$

Actually, in some devices, it was found that the gain at higher frequency over 5 GHz is not sufficient high, which can be enhanced by adopting shallow trench process and the extrinsic base implantation adjustment. Considering that high gain at low bias current in SiGe HBT device is of prime concerns, this problem should be solved in further process.

V. Conclusion

With development of passive elements, several low noise amplifiers were successfully designed and fabricated for the purpose of evaluating the developed SiGe bipolar process using RPCVD process. The cutoff frequency and maximum oscillation frequency of SiGe HBT having the emitter size of 0.5x6.0 μm^2 were measured as about 45 and 35 GHz, respectively. The measured minimum noise figure and associated gain of 1.5 dB and 16 dB, respectively, at 1.8GHz consuming the collector current of 4.6 mA were obtained in the 10-finger device. Using the device the low noise amplifier was designed to have a peak gain about 21 dB at 1.8 GHz including all matching networks with current consumption of only 3 mA with a supply voltage of 3.0 V. The input and output return losses were measured as -5.0 dB and -10.9 dB, respectively.

References

[1] G. Chang, L. Jansson, K. Wang, J. Grilo, R. Montemayor, C. Hull, M. Lane, A.X. Estrada, M. Anderson, I. Galton, and S.V. Kishore, "A direct-conversion single-chip radio-modem for Bluetooth," in *Proc. IEEE ISSCC, 2002*, pp. 88-448.

[2] P. van Zeijl, J.-W.T. Eikenbroek, P.-P. Vervoort, S. Setty, J. Tangenherg, G. Shipton, E. Kooistra, I.C. Keekstra, D. Belot, K. Visser, E. Bosma, and S.C. Blaakmeer, "A Bluetooth radio in 0.18-µm CMOS," *IEEE Trans. Solid-State Circuits*, vol. 37, pp. 1679-1687, 2002.

[3] D. L. Harame, J. M. C. Stork, G. L. Patton, S. S. Iyer, B. S. Meyerson, G. J. Scilla, E. F. Crabbe, and E. Ganin, "High performance Si and SiGe-base p-n-p transistors," in *Proc. IEEE IEDM*, 1988. pp. 889-891.

[4] S. J. Jeng, B. Jagannathan, J. -S. Rieh, J. Johnson, K. T. Schonenberg, D. Greenberg, A. Stricker, H. Chen, M. Khater, D. Ahlgren, G. Freeman, K. Stein, and S. Subbanna, "A 210-GHz f_T SiGe HBT with a non-self-aligned structure," *IEEE Electron Device Letters*, vol. 22, pp. 542-544, 2001.

[5] G. Freeman, J. -S. Rieh, B. Jagannathan, Zhijian Yang, F. Guarin, A. Joseph, and D. Ahlgren, "SiGe HBT performance and reliability trends through f_T of 350GHz," in *Proc. Reliability Physics Symposium*, 2003. pp. 332-338.

[6] Bin Li, S. Prasad, Li-Wu Yang, and S. C. Wang, "A semianalytical parameter-extraction procedure for HBT equivalent circuit," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-46, pp. 1427-1435, 1998.

[7] Ce-Jun Wei and J. C. M. Hwang, "Direct extraction of equivalent circuit parameters for heterojunction bipolar transistors," *IEEE Trans. Microwave Theory and Techniques,* vol. MTT-43, pp. 2035-2040, 1995.

[8] L. S. Vempati, J. D. Cressler, J. A. Babcock, R. C. Jaeger, and D. L. Harame, "Low-frequency noise in UHV/CVD Si- and SiGe-base bipolar transistors," in *Proc. IEEE BCTM*, 1995, pp. 129-132.

[9] Bongki Mheen, Dongwoo Suh, Sang Hoon Kim, Kyu-Hwan Shim, Jin-Yeong Kang, Songcheol Hong, "The enhancement of Q factor in RPCVD SiGe varactors by the structural modification of the base-collector junction," *IEEE Electron Device Letters* , vol. EDL-24, pp. 239-241, 2003.

[10] M. C. A. M. Koolen, J. A. M. Geelen, and M. P. J. G. Versleijen, "An Improved De-embedding Technique for On-Wafer High-Frequency Characterization", in *Proc. IEEE BCTM*, 1991, pp. 188-191.

[11] T.-H. Han, D.-H. Cho, S.-M. Lee, and B.R. Ryum, "Atmospheric pressure CVD-grown SiGe base HBT with the highest value of current gain-Early voltage product," in *Proc. IEEE TENCON '95*, 1995, pp. 408-411.