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Implementation of GaAs Monolithic Microwave Integrated Circuits with On-Chip BST Capacitors

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Abstract. GaAs microwave monolithic ICs with novel on-chip BST $(Ba_xSr_{1-x}TiO_3)$ capacitors are demonstrated. MOD (Metal Organic Decomposition) technique was employed to make the BST thin film. The fabricated BST capacitor has the dielectric constant as high as 300, which is 50 times higher than the conventional Si_3N_4 one. The implemented GaAs MMIC with on-chip BST capacitor provides both high gain and low power dissipation characteristics. These MMIC can be packaged in a compact outline with reduced pin counts. BST capacitors also show the suppressed harmonics due to their low-pass filtering characteristics of the frequency roll-off around 2 GHz. The present technology will reduce the system size for a variety of the mobile communication systems.

Keywords: BST, GaAs, MMIC, MOD

1. Introduction

There are growing demands in GaAs semiconductor devices in several information systems such as mobile communications [1,2], DBS (Direct Broadcasting Satellite) [3], and CATV systems [4] owing to their inherent low-noise and low-distortion characteristics in the microwave frequency range. Especially, in mobile communication systems, reducing the number of components with reduced footprint is most important to realize the compact handy-phone. The key for implementing such systems is to develop the GaAs MMIC (Monolithic Microwave IC) with large-scale-integration, because miniaturizing the RF systems is quite difficult as long as discrete components are used. One of the difficulties comes from integrating large capacitors, which consumes the largest area in the chip. This is serious in GaAs MMICs because the real-estate of GaAs is much more expensive when it is compared to silicon. Introducing ceramic materials with high dielectric constant for integrating large capacitors will make the break-through to implement the compact GaAs MMIC at a reasonable price. This is the motivation of our work.

2. History

Much work has been devoted so far to industrialize the ceramic materials since the discovery of ferro-electricity in Rochelle salt in 1920. Ferroelectric materials have many technologically interesting features such as spontaneous polarization, high dielectric constant, pyroelectricity, and piezoelectricity. So the study of those materials has been started aiming at the applications to electronics in the very early stage in the history as shown in Fig. 1. At present, the results have been put into production as various types of ceramic capacitors, RF filters [5], or special IR sensors [6]. On the other hand, semi-conductor technology went down the direction of miniaturization that attained high functionality in a single chip. In the late 1980s, there arose the technological movement of integrating the novel materials represented by PZT film as a storage capacitor to make non-volatile memory. This approach breaks through the scaling limit of the miniaturization by introducing a functional material.

Ferroelectric materials have useful features, namely high permittivity, which typically ranges

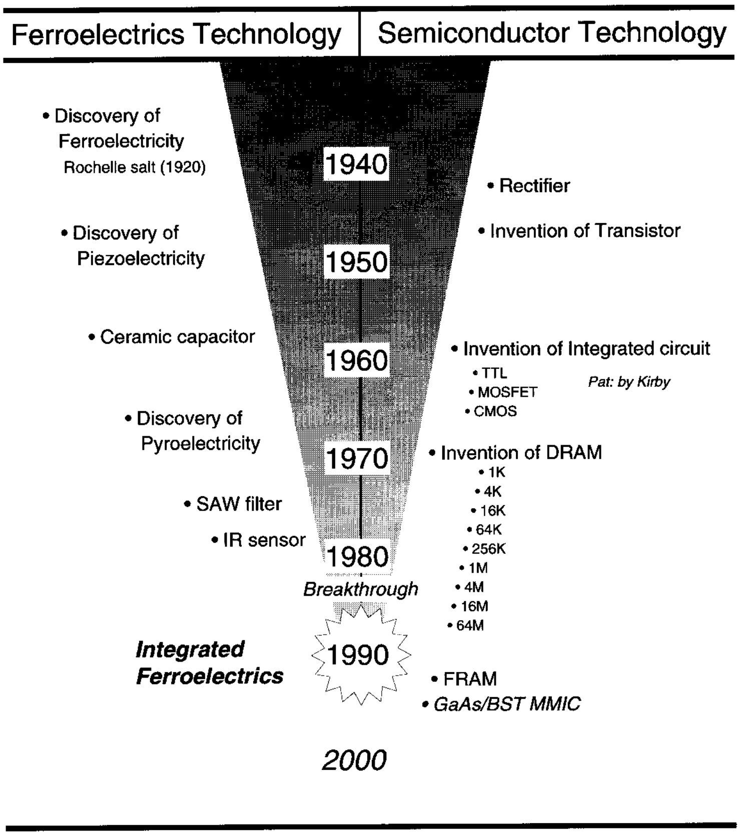

Fig. 1. Evolution of ceramic and semiconductor technologies.

from several hundreds to thousands. This factor is more than two or three orders of magnitude higher than conventional Si_3N_4 capacitors that are widely used in integrated circuits.

The joint-project started in April 1992 with Prof. C. P. Araujo, University of Colorado, Colorado Springs, who provided the solution to make thin film capacitors by using a unique MOD (Metal Organic Decomposition) technique [7]. In order to achieve the high frequency operation in L-band (800 MHz–2.4 GHz), where the major mobile communication systems are available, we chose the material BST ($Ba_xSr_{1-x}TiO_3$). In February 1993, we developed three types of GaAs MMICs with on-chip BST capacitors for the cellular phone-set, which opened the new era of GaAs history [8]. At present (1998), those IC have populated more than 20 categories designed for many communication systems.

3. How BST Capacitors are used in the Microwave Circuit

Although GaAs FETs have a superior high-frequency performance, they only have depletion-mode characteristics due to the extremely high surface-state density of the semiconductor [9]. Negative-bias supply is required to pinch-off the drain current, which causes complexity in the driving circuits. Putting a small resistor between the source and ground is a common method to enable single voltage operation, however, simply placing source resistor degrades both gain and noise performances of the RF amplifier. Adding bypassing capacitors in parallel is necessary to avoid such RF degradation. It is noted that multiple bypassing capacitors with different frequency characteristics are usually used to obtain sufficiently low impedance to ground. If you try to integrate such capacitors using conventional SiN films (dielectric constant 6.5), the consumed area will be too large to afford the die cost. For that reason, conventional MMIC are usually provided with external pins to connect the capacitors outside the package, which ends up in increasing the package-size with many external pins and increasing the mounting area as illustrated in Fig. 2.

Unexpectedly, we found that the RF gain can be increased by integrating the on-chip BST capacitor [10]. The reason is shown in Fig. 3. The impedance between the source and the ground can be reduced to the limit of the residual inductance originated from the bonding-wire and lead-frame. This residual inductance causes undesirable negative feedback of the circuits so that the obtainable RF gain is decreased, while the circuit with on-chip bypass capacitor is free from such effects owing to the ground inside the chip. Figure 4 shows the gain comparison of the LNAs (low Noise Amplifier) with and without on-chip capacitors. You can see at least 9 dB gain increase in case of using on-chip capacitors. As is generally known that the higher gain can be obtained by increasing the dissipation current, the new GaAs MMIC with on-chip capacitor will lower the operation current keeping the same gain as shown in Fig. 5.

4. Fabrication of BST Capacitor

Ferroelectric materials have high dielectric constants and ferroelectricity due to spontaneous polarization. However, in case of using ferroelectric materials in GaAs MMIC, this spontaneous polarization causes RF loss by the hysteresis under alternating electric field. We employed the material $Ba_xSr_{1-x}TiO_3$(BST), which is the mixed crystal of $BaTiO_3$(BTO) and $SrTiO_3$(STO). Although bulk BTO has extremely high dielectric constant, it has a tetragonal crystal structure which shows E-D hysteresis at room temperature. On the contrary, STO does not have such hysteresis characteristics due to its cubic crystal structure, though it has lower dielectric constant than BTO. The dielectric constant of the mixed crystal of BST increases as the ratio x (BTO mole fraction) increases.

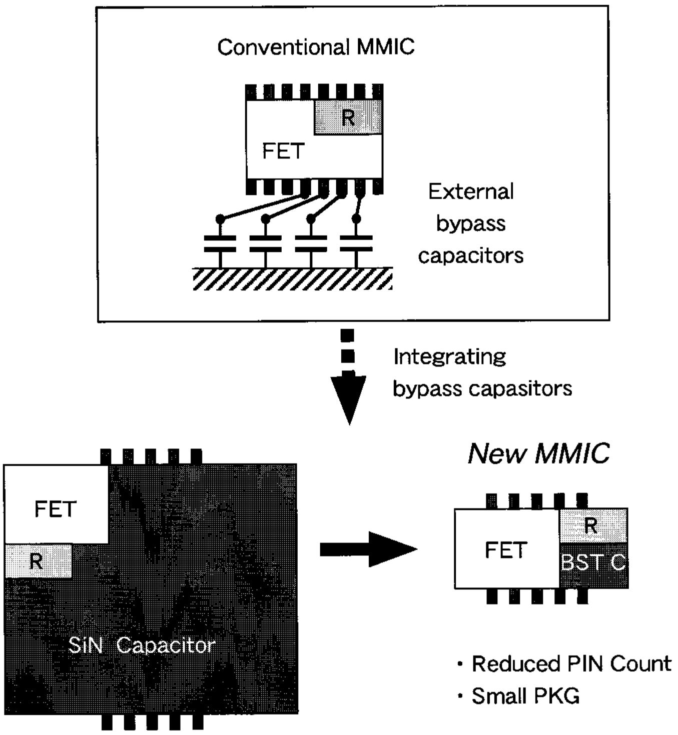

Fig. 2. Area comparison of MMIC in case of using SiN and BST capacitors.

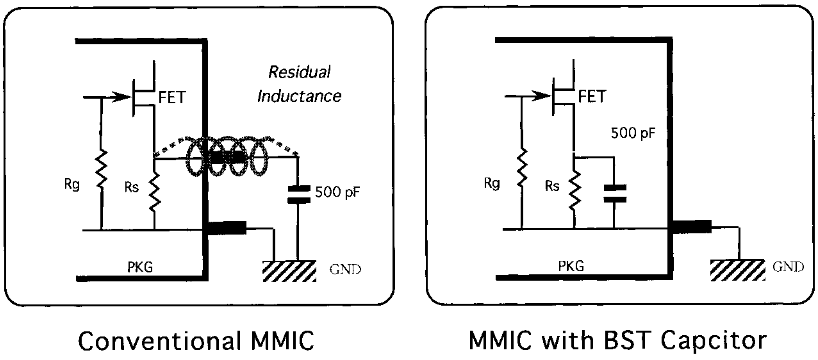

Fig. 3. Schematic equivalent circuits for cases of external and internal bypass capacitors.

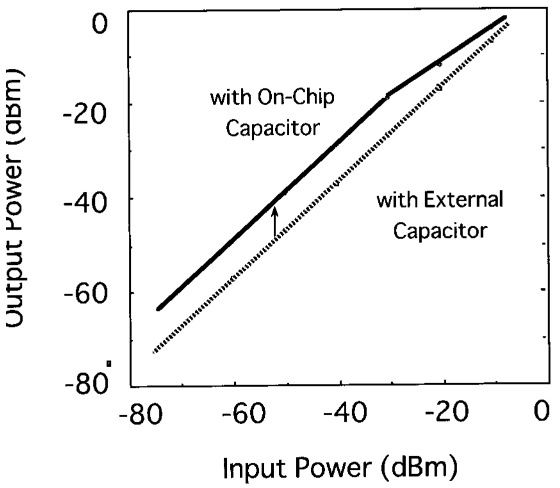

Fig. 4. RF characteristics for cases with internal and external bypass capacitors.

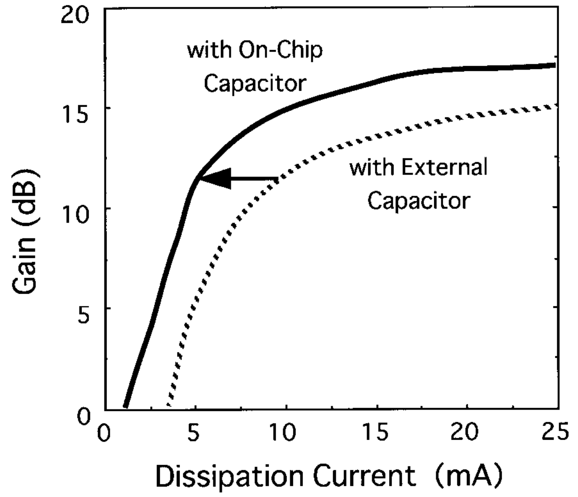

Fig. 5. Obtainable RF gain v.s. drain current of GaAs FET amplifier.

As shown in Fig. 6, we chose $x = 0.7$, where the highest dielectric constant can be obtained without E-D hysteresis, since the bulk crystal structure of BST is cubic when x is less than 0.7 at room temperature.

The MOD technique, where Ba, Sr and Ti organometallic precursors are spin-coated, allows precise composition control of those elements by chemical synthesis. This methodology is superior to the other methods like RF-sputtering or CVD in view of repeatability and cost-reduction because no expensive process facility is needed.

The fabrication procedure of the MMIC is shown in Fig. 7. At first, the bottom Ti/Pt electrode was formed by using EB evaporation over the GaAs wafer where active regions are already formed. It is noted that platinum electrodes are chosen for both the bottom and top electrodes because they are refractive, free from oxidation, nor form intermixed layers in the vicinities of the BST film. After spin-coating, the MOD solution over the Pt electrode, the initial drying was carried out at the temperature at 200°C in ambient atmosphere followed by the annealing at over 600°C in an oxygen ambient. The resultant thickness of the BST film was 200 nm. The crystallinity as well as the dielectric constant of the BST capacitor goes higher as the annealing temperature is increased. Then, the BST film and the electrodes were patterned by using the ion-milling technique. After metallizing each device using Au electroplating, the wafer was finally passivated by SiN film.

The frequency dispersion characteristics and the temperature coefficient of the capacitor are important in designing practical RF integrated circuits. We found frequency roll-off characteristics of the BST

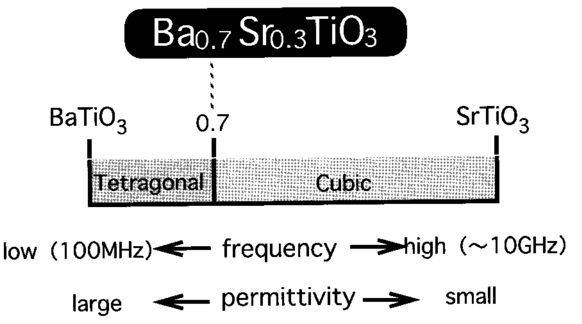

Fig. 6. Phase transition of $(Ba_xSr_{1-x}TiO_3)$ crystal structure.

capacitor is dependent on the annealing temperature. The capacitance and the leakage current was extracted by the s-parameter measurement using a network analyzer. Figure 8 shows the frequency dispersion characteristics of a BST capacitor annealed at different temperatures. You can see that the dielectric constant is more than 300 with frequency roll-off over to 2 GHz in case of annealing at 700°C. We determined the appropriate annealing temperature by the required frequency range of the specific application. It is noted that the obtained leakage current is less than 5×10^{-7} A/cm^2.

The measured temperature coefficient is less than 500 ppm/C. It is noted that no phase transition was observed in the temperature range from −50 to 150°C. This is presumably due to the suppression of phase transition of the BST film deposited over well-oriented Pt electrodes.

Figure 9 shows the reliability of BST capacitors under the BT (bias and temperature) test. You can see stable capacitance characteristics over 1000 h after the initial small drop of less than 5%. The reliability of the fabricated capacitors was evaluated by TDDB (Time Dependent Dielectric Breakdown) measurement under BT stress to forecast the lifetime. TDDB measurement was done under the conditions of the three different bias stresses at the temperature of 125°C. The cumulative failure was obtained by counting the number of the destroyed capacitors out of 20 capacitors with measuring time. Figure 10 shows the time dependence of the cumulative failure (i.e., Weibull plot) of the fabricated BST capacitors. MTTF (Mean Time To Failure) under each condition can be estimated by a simple statistical calculation by the parameters obtained from the plotted-lines. Figure 11 shows the relationship between MTTF and the 1/E (inverse of the electric field applied to the capacitors) at 125°C. Under the bias of 10 V at the temperature of 125°C, MTTF of the present BST capacitor was estimated to be 10^4h [11,12]. The predicted lifetime will be over 10^{12} h when the practical bias-voltage is less than 5 V. This is good enough to be applied to almost all the integrated circuits for the consumer market.

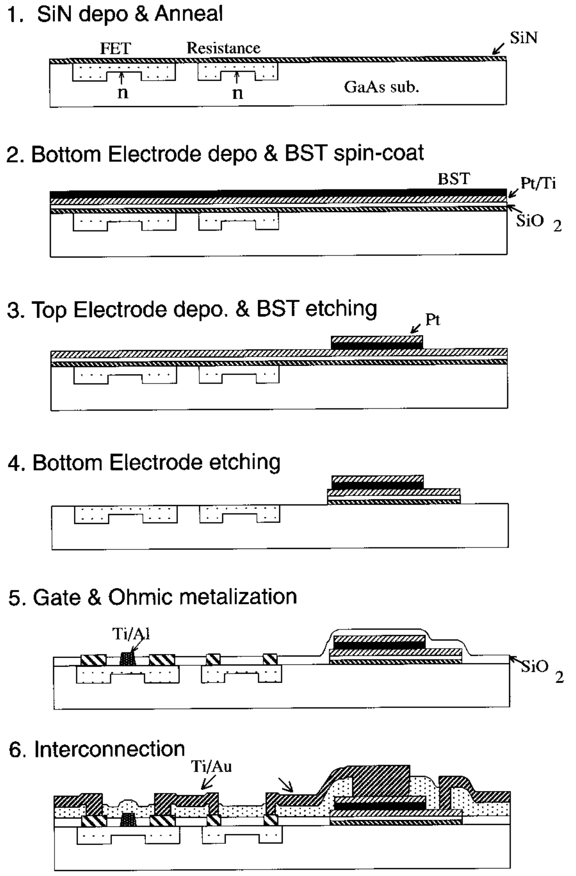

Fig. 7. Process flow of GaAs MMIC with on-chip BST capacitor.

5. GaAs MMICs with On-Chip BST Capacitor

Figure 12 shows a schematic block diagram of typical digital cellular phone-set. GaAs devices are the key component in RF blocks such as LNA, Mixer, and Switch ICs. There are two major roles of the BST capacitor in GaAs MMIC. One is for the bypassing capacitor to make single voltage operation, the other is the coupling capacitor to transfer the RF signal with DC-decoupling that is usually placed at both the input and output of those blocks.

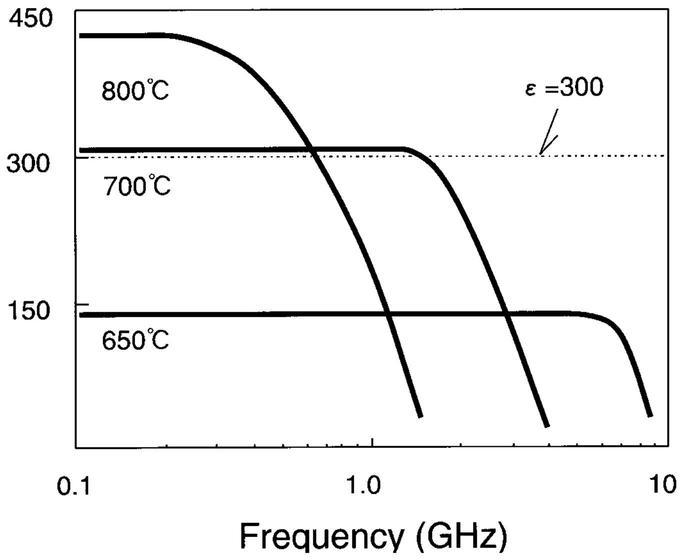

Fig. 8. Frequency dispersion characteristics of fabricated BST capacitors with different annealing temperatures.

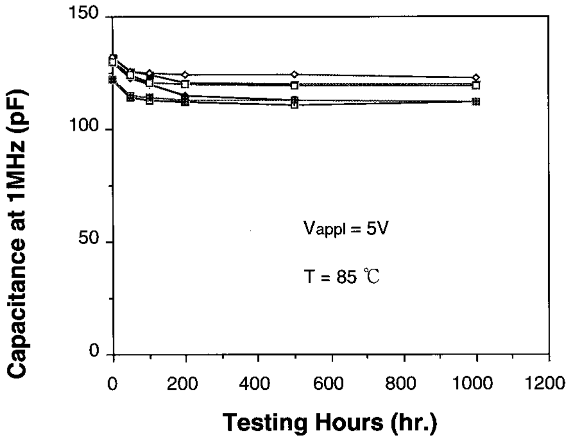

Fig. 9. Capacitance BT test of fabricated on-chip BST capacitors.

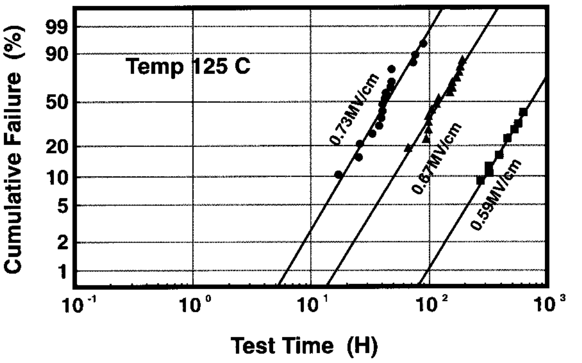

Fig. 10. TDDB results under different bias condition at the temperature of 125°C.

5.1. Bypass Capacitor for GaAs MMIC

The major role of BST capacitors is the bypass capacitors. The circuit configuration of the LNA (with diversity switching capability) is shown in Fig. 13(a) [13]. This diversity switching capability is to select a stronger signal out of two RF input signals to avoid the fading problem. The LNA consists of two dual-gate MESFET's, a common source-bias resistor with the BST bypass capacitor, and Zener diodes for surge protection. The source resistance is designed so that the gate-source voltage of the off-state FET is biased below the pinch-off voltage. The capacitance of this common-source capacitor is 800 pF. This selection is done by applying complementary control voltages to the second gates of two MESFET's. It is noted that the switching voltage at the ON state and the OFF state is set as 2 V and 0 V, respectively, where no negative voltage-control voltage is needed. The photographs of the fabricated LNA is shown in Fig. 13(b).

The LNA is mounted in the 6-pin mini-package, which required at least 8 pins so far at the periphery. Figure 13(c) shows the typical frequency characteristics of the gain and NF (noise figure) for the LNA. As shown in the figure, the gain of 16 dB, the NF of

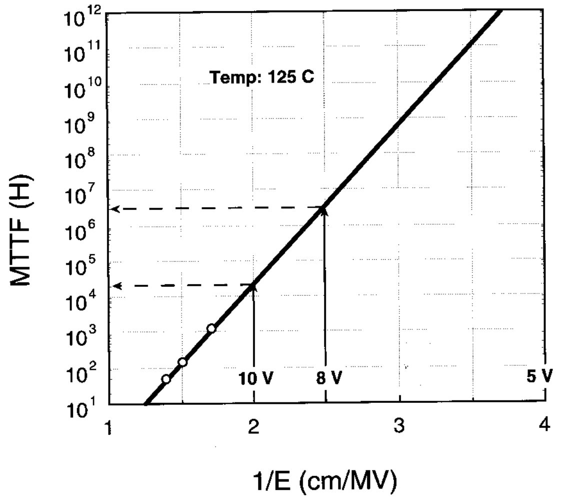

Fig. 11. Relationship between MTTF and applied electric field to BST capacitor.

2.2 dB, and the switching isolation of more than 25 dB are attained at the dissipation current of 3 mA.

5.2. *Coupling Capacitor for GaAs MMIC*

The SPDT or DPDT switch is widely used as a receiving/transmitting switch in TDMA (Time Divide Multiple Access) systems. Although the conventional GaAs monolithic switch IC can operate at almost zero power dissipation, the IC increases the insertion-loss as the transmitting power is increased. In order to improve the power handling capability of the switch, we devised the synchronized voltage superposition to the gate of FET1 and FET4 by the BST capacitor. Figure 14(a) shows our SPDT switch circuit IC with on-chip BST capacitor that has high power handling capability [14]. This feed-forward configuration can be achieved by the capacitor with a diode connected in series between the gates of FET1/FET4 and RF terminals. This synchronous voltage superposition avoids the clipping of the output waveform so that the handling power is increased. Since the input, output, and ground terminals are capacitor-coupled, needless to say, the present GaAs switch IC requires no negative voltages to control.

Owing to the BST capacitor technology, five 100 pF coupling capacitors and two 10 pF feed-forward capacitors are integrated in a small chip area as shown in the photograph of Fig. 14(b). Figure 14(c) shows the P1 dB as a function of the control voltage. Measured P1 dB of conventional SPDT switch IC without the feed-forward circuit are also plotted in the same figure. Even at the control voltage of 3 V, the P1 dB over 37 dBm can be achieved. It is noted that the harmonics are well suppressed by the

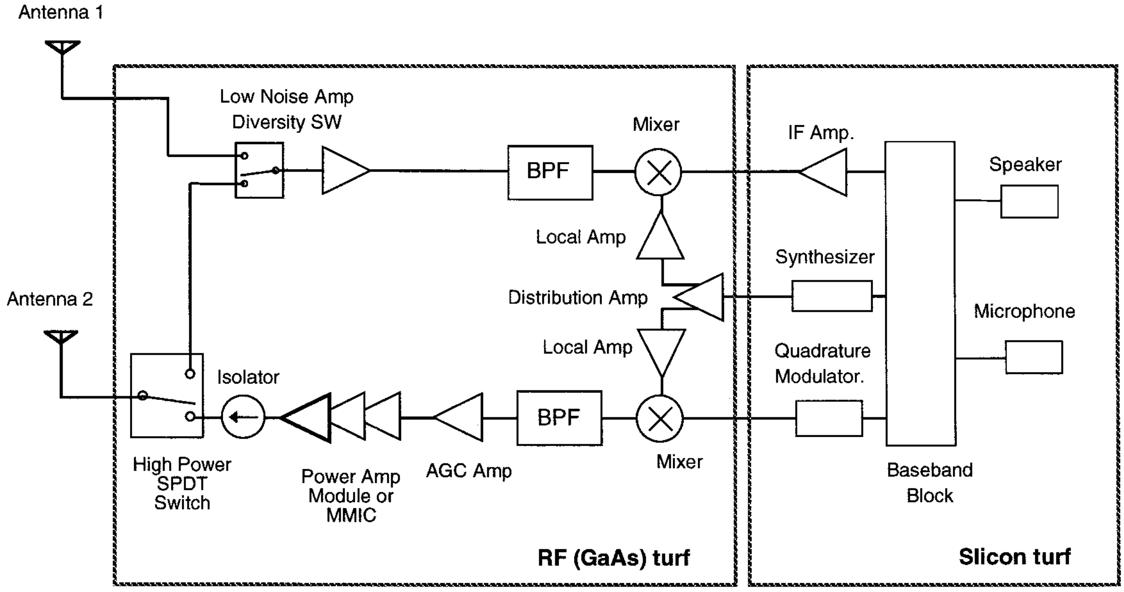

Fig. 12. Typical block diagram of digital cellular phone set.

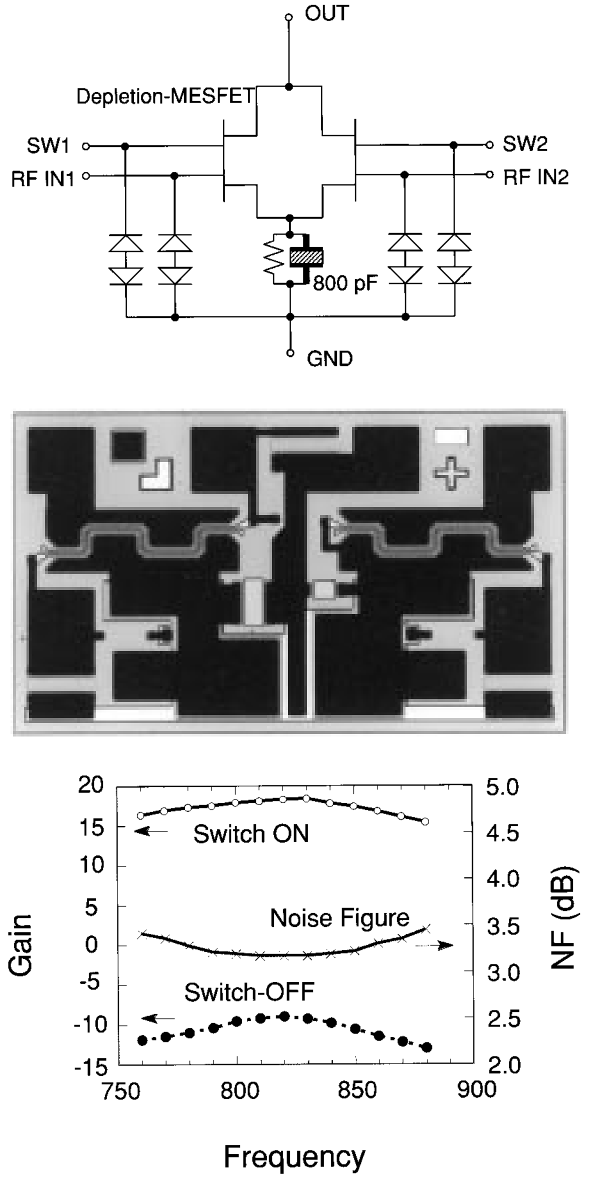

Fig. 13. (a) Circuit configuration of dual-LNA with BST bypass capacitor, (b) Chip photo-micrograph of dual LNA (GN1048), (c) RF performance of dual LNA.

frequency roll-off characteristics of the BST capacitor, which is another feature of the present BST capacitor of low-pass filtering characteristics.

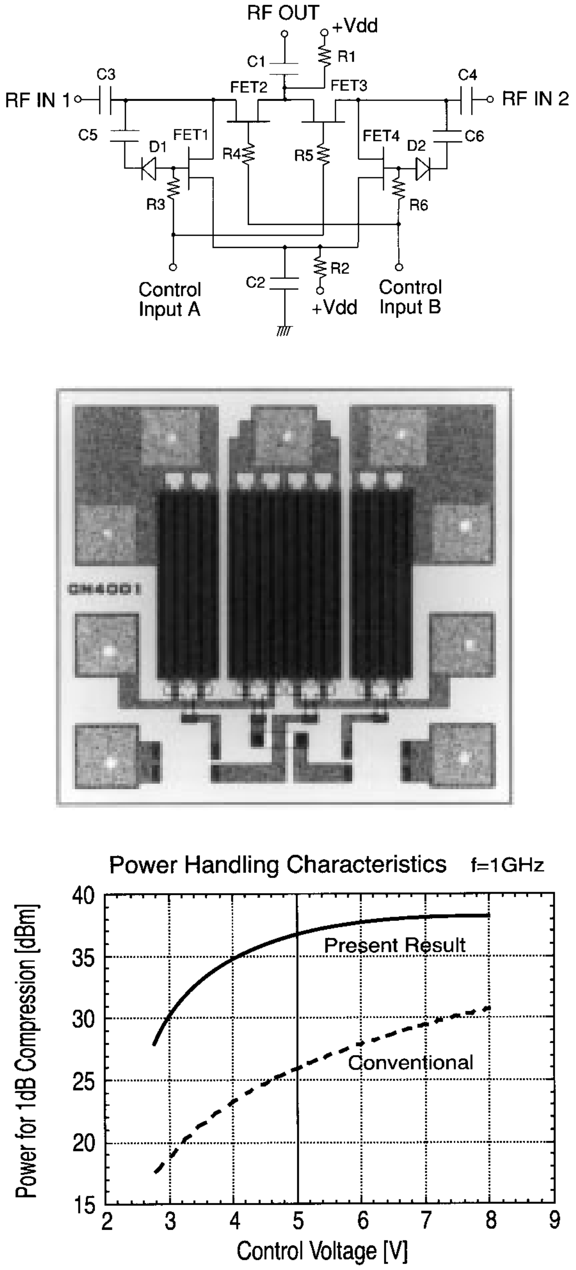

Fig. 14. (a) Circuit configuration of high-power SPDT switch IC with BST capacitor, (b) Chip photo-micrograph of high-power SPDT switch IC (GN4004), (c) Comparison of power handling capability of fabricated SPDT switch IC and conventional one.

6. Conclusion

We demonstrated a technology for integrating on-chip BST capacitors in the GaAs MMICs, where $Ba_{0.7}Sr_{0.3}TiO_3$(BST) film was formed by the MOD technique. The fabricated BST capacitor has attained a dielectric constant of 300 with frequency roll-off over 2 GHz. This factor is 50 times higher than that for the conventionally used SiN one. The forecasted

MTTF is estimated over 10^{12} h by the TDDB measurement with supply voltage less than 5 V at 125°C. The MMICs is dramatically reduces the chip-size, package-pin-counts, and eventually the system size. The IC amplifiers with BST capacitor achieved higher gain with lower dissipation current compared to one without it. The GaAs MMICs with on-chip BST capacitor are applicable for a variety of information systems. [15–17].

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