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K-band Si/SiGe HBT MMIC Amplifiers Using Lumped Passive Components with a Micromachined Structure.

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Abstract

Using Si/SiGe heterojunction bipolar transistors with a maximum oscillation frequency of 52 GHz and a novel structure for passive components, a two-stage K-band lumped-element amplifier has been designed and fabricated on high-resistivity Si substrates. The chip size including biasing and RF chokes is 0.92×0.67 mm^2.

Introduction

With recent advances in the epitaxial growth of silicon-germanium heterostructures, the concept of high-performance and high-frequency electronic devices compatible with advanced silicon technology has been realized. The Si/SiGe heterojunction bipolar transistors (HBTs) have received the greatest attention[1][2]. Recently, monolithic microwave and millimeter wave integrated circuits (MMICs) based on Si/SiGe HBTs and distributed circuit components have been presented[3][4].

In this work, we have developed the fabrication technologies for Si/SiGe HBT on high-resistivity Si substrates. For a5×5 μm^2 emitter size, a 28 GHz cut-off frequency and a maximum oscillation frequency of 52 GHz was demonstrated. In addition, lumped coplanar novel micromachined passive components characterized by high resonant frequencies are also modeled and fabricated. By integrating these passive components into the HBT fabricating process, the application range of Si MMICs with lumped elements can be extended even above 30 GHz. K-band lumped amplifiers using these micromachined passive components have been designed and fabricated based on the Si/SiGe HBTs.

Si/SiGe HBTs

Active devices are the most crucial components that determine the overall performance of microwave circuits. Optimized structure, high quality epitaxial layers, and stable processing technology are the key to successful development of high performance devices for high-frequency circuit applications. We have designed and grown npn double heterojunction Si/SiGe HBT structures by molecular beam epitaxy (MBE). The HBT structure is shown in Fig. 1. The substrate is Si with a resistivity of ρ~10 kΩcm, which is high enough to suppress the substrate-originated ohmic loss for passive components in microwave circuit applications[5]. First, As-doped subcollector is formed by chemical vapor deposition, then the other epitaxial layers are grown by MBE. The growth temperature is fixed at 415 °C for the collector and emitter layers, and 550 °C for the base layer. Emitter and col-

n+ Si	emitter contact	2×10^{19} cm^{-3}	2000 Å
n Si	emitter	2×10^{18} cm^{-3}	1000 Å
i $Si_{0.6}Ge_{0.4}$			50 Å
p+ $Si_{0.6}Ge_{0.4}$	base	2×10^{19} cm^{-3}	200 Å
i $Si_{0.6}Ge_{0.4}$			50 Å
n- Si	collector	5×10^{15} cm^{-3}	3000 Å
n+ Si	sub-collector	1×10^{19} cm^{-3}	15000 Å
p- Si	substrate	1×10^{12} cm^{-3}	540 µm

Figure 1. Si/SiGe HBT material structure

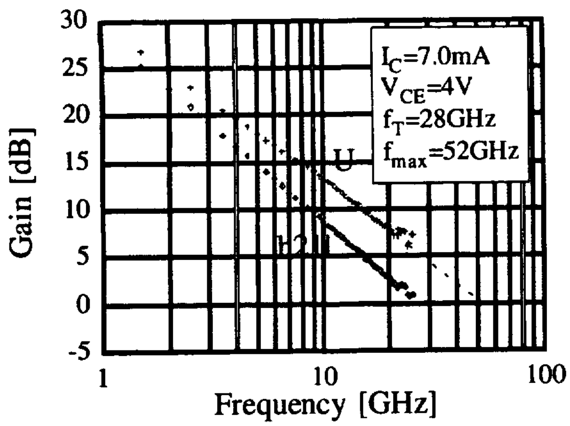
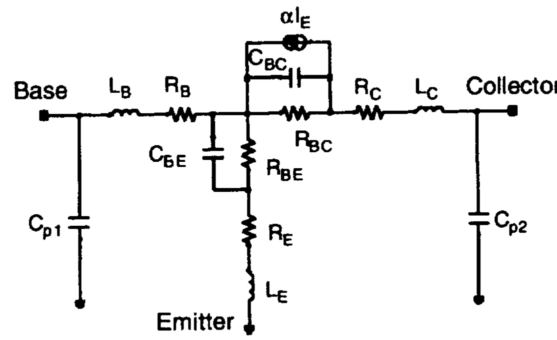


Figure 2. Frequency response of Si/SiGe HBT (A_E=5×5 μm^2)



R_B	13.1 Ω	R_{BC}	127.0 kΩ
L_B	62.6 pH	C_{BC}	28.9 fF
R_{BE}	1.0 Ω	R_C	24.8 Ω
C_{BE}	106.8 fF	L_C	66.1 pH
R_E	15.8 Ω	$C_{p1,2}$	4.0 fF
L_E	141.7 pH	α_o	0.995

Figure 3. Small signal equivalent circuit and parameters

lector layers are Sb-doped Si, while the base layer is B-doped SiGe alloy with a uniform Ge mole fraction of 40%. The doping concentration and thickness of the base layer are 2×10^{19} cm^{-3} and 200 Å, respectively. Unintentionally doped spacer layers are inserted at E-B and B-C junction to minimize the effect of boron outdiffusion.

Mesa-type HBTs have been fabricated with a standard lift-off and etching techniques. Emitter contact is formed by a Cr/Au metal layer, while base and collector contacts are made with Pt/Au and Ti/Au, respectively. Rapid thermal annealing (RTA) is performed after metal deposition to reduce the contact resistance of these electrodes. Base and collector mesa are formed with SF_6 and O_2-based reactive ion etch (RIE). Emitter mesa formation, which exposes the base layer for metalization, is the most critical step in the fabrication process of mesa-type HBTs since this process directly affects the f_{max} of the devices through the parasitic base resistance R_B Over-etching of the base layer and undercutting of emitter layer should be minimized to keep the value of R_B small. To achieve this, we use a two-step etch. First, an anisotropic RIE step removes most of the emitter layer without undercut. Second, a KOH-based solution selectively etches the remaining emitter layer and stops close to the E-B junction. This also introduces minimal undercut for self-aligned base metal deposition. SiO_2 passivation, via hole formation, and interconnection metal deposition for probe pads complete the whole process.

DC and RF characteristics of the Si/SiGe HBTs have been measured and analyzed. The devices have an emitter area A_E=5×5 μm^2 and a B-C junction area A_{BC}=12×13 μm^2. The DC current gain β has been measured to be higher than 100, and the collector and base ideality factors have been extracted to be n_c=1.04 and n_B=1.79, respectively. From the measured scattering parameters with an 8510B network analyzer, we have obtained the frequency response and have extracted the small signal equivalent circuit parameters of the device. Figure 2 shows its current gain and unilateral power gain. The f_T and f_{max} obtained from the extrapolation of the gain values at 20 GHz with the assumption of a -6 dB/octave roll-off, are 28 GHz and 52 GHz, respectively, at the bias point of I_C=7 mA and V_{CE}=4 V. A small signal equivalent circuit and parameters of the device at the identical operating point are shown in Figure 3.

Passive Components

Planar lumped inductors are widely used in MMIC as matching elements, bias chokes and filter components. Compared with distributed transmis-

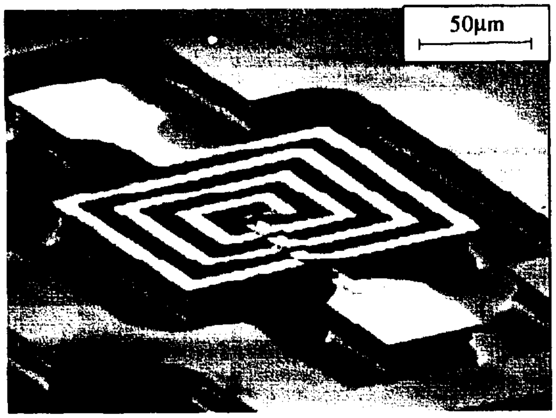


Figure 4. Photomicrograph of the micromachined spiral inductor

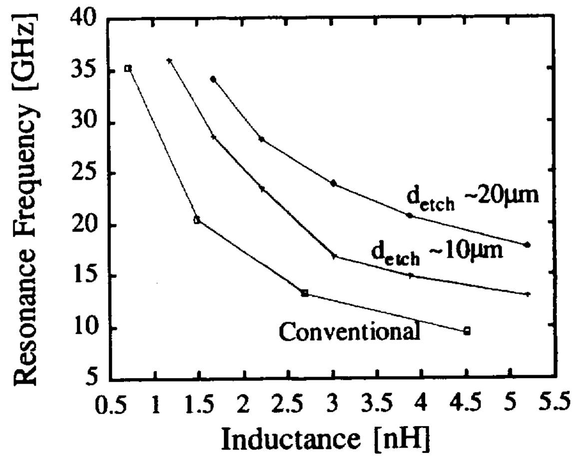


Figure 5. Resonant frequencies of inductors with various etch depth, d_{etch}.

sion line elements, lumped elements are smaller, especially at frequencies below 30 GHz. As a result, lumped element circuits can be more compact than distributed ones in MMIC applications. However, planar lumped elements suffer from parasitic capacitance. Specifically, planar lumped inductors exhibit very low resonant frequencies due to the parasitic capacitance, thus limiting operating frequencies. Work has been done by fabricating the inductors on dielectric membrane to increase the resonant frequency[6][7]. This approach is difficult to be integrated with active devices since it requires the development of a dielectric membrane between the bulk high-resistivity Si and the doped layers. To avoid this difficulty, a new micromachined spiral inductor has been developed as shown in Fig. 4. By covering the metal structure with Ni which is used as a self-aligned mask and removing the substrate material in between the turns by RIE, the effective dielectric constant of this structure can be reduced. This results in a smaller series and shunt parasitic capacitance from turn to turn and from the signal line to ground. Due to the significant reduction of the parasitics, the resonant frequency can be increased drastically. In the measurement, the resonant frequency increases from 20 GHz to 38 GHz for a 1.5 nH spiral inductor by using this micromachined structure. The complete measurement results for the micromachined spiral inductors with various inductance and etching depth are shown in Fig. 5. Other passive components are also integrated into the processes and modeled for the circuit design. A 2000 Å SiO layer is used as the dielectric material for MIM capacitors. The extracted dielectric constant ε_r is 4.7 which provides a capacitance of 0.21 fFμm^2. For thin film resistors (TFRs), a NiCr layer of 700 Å is used and gives a sheet resistance of 25~30Ω/□.

HBT Amplifier Circuits

Using coplanar waveguides, a two-stage lumped amplifier as shown in Fig. 6 is designed and fabricated. It consists two :> 5μm^2 Si/SiGe HBTs. Micromachined spiral inductors, MIM capacitors and TFRs are used for the matching network, transistor biasing and RF blocks, and the

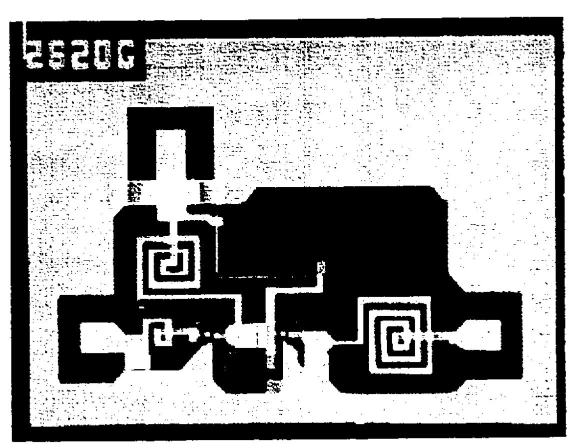


Figure 6. Photomicrograph of the fabricated two-stage amplifier. The chip size is 0.92×0.67mm^2

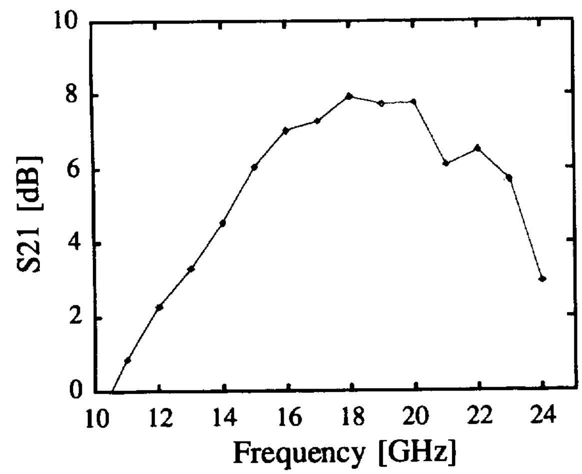


Figure 7. Simulated S21 of the two-stage amplifier

chip size of the circuit is 0.9: : 0.67 mm. From simulation results, this two-stage amplifier provides the maximum gain of 8.2 dB at 20 GHz with a bandwidth of 43% as shown in Fig. 7. Fabrication of the circuits are in progress and their measured characteristics will be presented and discussed.

Conclusion

By developing the micromachined passive components with higher resonant frequencies and integrating them into Si/SiGe HBT process, it is possible to implement Si based MMIC for higher frequencies using a lumped design concept. A two-stage K-band amplifier has been demonstrated, and the same technology can also apply for other MMIC applications.

Acknowledgment

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