THE DEVELOPMENT OF Si AND SiGe TECHNOLOGIES FOR MICROWAVE AND MILLIMETER-WAVE INTEGRATED CIRCUITS

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INTRODUCTION

Historically, microwave technology was developed by military and space agencies from around the world to satisfy their unique radar, communication, and science applications. Throughout this development phase, the sole goal was to improve the performance of the microwave circuits and components comprising the systems. For example, power amplifiers with output powers of several watts over broad bandwidths, low noise amplifiers with noise figures as low as 3 dB at 94 GHz, stable oscillators with low noise characteristics and high output power, and electronically steerable antennas were required. In addition, the reliability of the systems had to be increased because of the high monetary and human cost if a failure occurred.

To achieve these goals, industry, academia, and the government agencies supporting them chose to develop technologies with the greatest possibility of surpassing the state of the art performance. Thus, Si, which was already widely used for digital circuits but had material characteristics that were perceived to limit its high frequency performance, was bypassed for a progression of devices starting with GaAs Metal Semiconductor Field Effect Transistors (MESFETs) and ending with InP Psuedomorphic High Electron Mobility Transistors (PHEMTs). For each new material or device structure, the electron mobility increased, and therefore, the high frequency characteristics of the device were improved. In addition, ultra small geometry lithographic processes were developed to reduce the gate length to 0.1 μm which further increases the cutoff frequency. The resulting devices had excellent performance through the millimeter-wave spectrum.

Initially, the use of exotic materials with small geometry lithography resulted in poor yields. Therefore, early circuits were fabricated by bonding the transistors to ceramic substrates such as alumina upon which the matching circuits were built. As the processing technology matured and yield improved, Microwave Monolithic Integrated Circuits (MMICs) became possible. This higher level of integration reduced the circuit size and the

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parasitic reactance created by the wire bonds which led to further improvements in the circuit characteristics. Today, GaAs and InP MESFET, PHEMT, and Heterojunction Bipolar Transistor (HBT) based MMICs have RF characteristics that are sufficient for nearly every application.

Unfortunately for the GaAs industry, the market for microwave circuits has changed dramatically over the past three years. While government agencies continue to buy circuits for their needs, the commercial market for personal communications, wireless communications, analog and digital mobile communications, intelligent vehicle highway systems, and industrial sensors has surpassed the military market. This has imposed a new requirement on the microwave industry; Once a circuit provides the needed service, cost is the most important parameter.

The exotic materials and small dimensions that yielded outstanding MMIC characteristics also resulted in high fabrication cost. In addition, since GaAs and InP circuit processing is not compatible with Si processing, they require separate and different equipment. Thus, the large capital investments made by the electronic industry and the corresponding low fabrication cost per silicon wafer area cannot be used by the GaAs MMIC industry, and these conditions are not expected to improve unless new markets develop for GaAs MMICs that would lower their fabrication cost. Lastly, higher levels of integration are not possible if MMICs are made from GaAs or InP and the data control and bias circuits are made from Si. Therefore, integration and packaging costs cannot be lowered and reliability improvements that are associated with integration cannot be realized.

To achieve lower cost and higher levels of integration, the microwave industry is reevaluating its reliance on GaAs and InP and the perceived disadvantages of Si which include poor high frequency performance due to low carrier mobility and high transmission line attenuation due to the low substrate resistivity. As silicon circuit manufacturers have reduced the gate size of their standard n-MOSFETs, Metal Oxide Field Effect Transistors, f_{max} has increased to 37 GHz [1], and self aligned Bipolar Junction Transistors (BJTs) have been fabricated with an f_{max} of 70 GHz [2]. More interesting though is the significant increase in microwave capabilities that arises from the introduction of Ge to create SiGe HBTs that have an f_{max} of 160 GHz [3]. These new devices should fulfill the requirements of the commercial industry through Ka-band, but further improvements are possible if the SiGe material structure and microwave component characteristics on Si are optimized.

This paper will present the efforts of research teams at NASA Lewis Research Center and The University of Michigan to grow higher quality SiGe on Si, characterize SiGe HBT material structures, and develop passive components on Si.

SiGe/Si HBT FABRICATION

High Ge content Si_xGe_{1-x} alloys (1-x>0.4) have a higher carrier velocity than Si that should translate into better microwave transistor characteristics[4], but there are practical limits to the Ge concentration. The most serious limitation comes from the fact that the Ge atomic lattice is 4.2 % larger than the Si lattice[5]. Therefore, strain is created within the lattice when SiGe is grown on a Si substrate, and the strain increases as the Ge content increases. If the strain reaches a critical value, misfit dislocations develop as is shown in the TEM micrograph in Figure 1. These thread type dislocation defects may degrade device performance, reliability, and fabrication yield if they terminate on or near the device channel. Thus, it is desirable to develop methods of reducing the defect density while maintaining a high Ge content.

Several authors have advocated the use of superlattices and graded structures that start with a very low Ge concentration at the SiGe/Si interface with increased Ge content as subsequent layers are added[6-11]. Although some reduction in misfit dislocations is obtained, the defect density is still too high[12] at approximately 10^9 cm^{-2} as seen in Figure 1. At the University of Michigan, an alternative approach that uses a low temperature silicon (LT-Si) buffer layer between the SiGe and the Si substrate has been developed[13]. This 0.1 μm thick layer is grown at 450 C by molecular beam epitaxy (MBE) followed by the SiGe HBT structure. It is seen in Figure 2 that the misfit dislocations are terminated in the LT-Si layer resulting in a defect density of <10^4 cm^{-2} at a thickness of 0.5 μm. The exact mechanism for the defect density reduction is currently unknown.

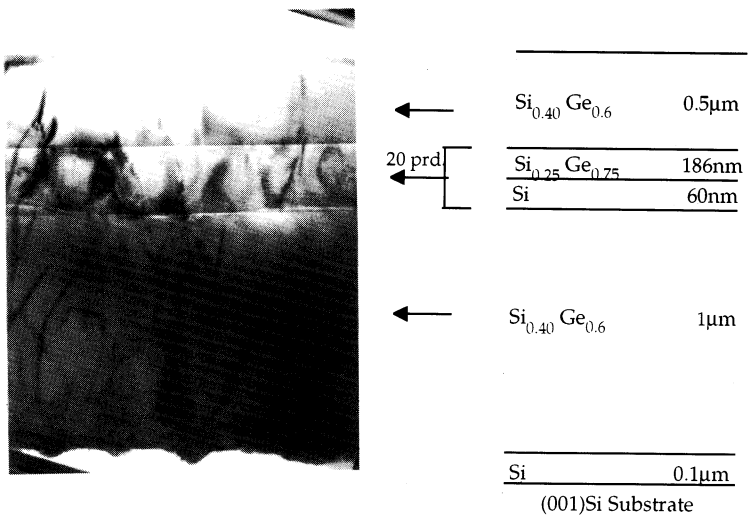

Figure 1. Cross-section TEM image of MBE grown SiGe heterostructure with 20 superlattices showing the dislocation propagation.

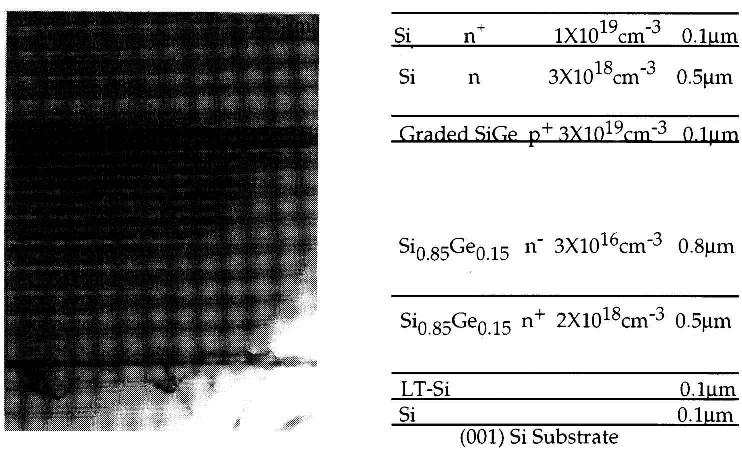

Figure 2. Cross-section TEM image of MBE grown SiGe HBT structure with LT-Si buffer layer showing the defect density reduction.

The structure shown in Figure 2 was used to fabricate self-aligned HBTs that incorporated Cr/Au contacts. As seen in the current-voltage curve for the 10 X 10 μm^2

device shown in Figure 3, the DC current gain is approximately 6, the breakdown voltage is greater than 10 V, and the Early voltage is approximately 1000 V. These results demonstrate that the LT-Si buffer does not degrade the DC characteristics of the HBT. Note that this device was not optimized for microwave performance.

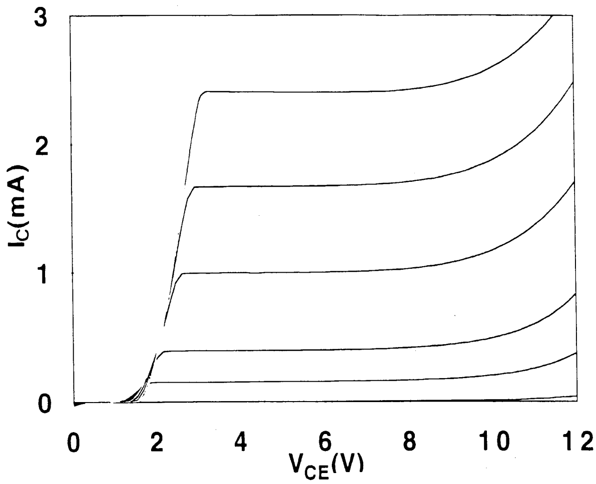

Figure 3. Measured current-voltage characteristics of 10X10 μm^2 emitter area HBT.

ELLIPSOMETRIC CHARACTERIZATION OF SiGe/Si HBT MATERIAL

Ellipsometry is an optical, non-destructive method to characterize semiconductor multilayers[14]. It uses dielectric calibration functions to interpret the experimental Ψ and Δ in terms of materials. Thus, accurate calibration functions are critical for materials studies. In this case, the dielectric functions of Si_xGe_{1-x} are known to high accuracy for the whole concentration range for relaxed material[15], but only very limited data is available for strained layers[16].

For a typical SiGe/Si HBT structure, ellipsometry is expected to estimate non-destructively the thickness of the emitter and base layers, the composition parameter x, and any dielectric layers on top of the emitter (thickness and dielectric constant). The ellipsometry work in this case is not straightforward, due to three problems: 1. The Si emitter layer is very thick; 2. There is strain in the Si_xGe_{1-x} base; 3. Usually there is a concentration gradient in the base layer. The first problem is due to the fact that the thick Si emitter layer is blocking the light below a wavelength of roughly 400 nm. However, many special features of the Si_xGe_{1-x} calibration functions are below 400 nm, thus decreasing the sensitivity for the x estimate. The second problem is due to the lack of accurate strained Si_xGe_{1-x} calibration functions, as mentioned above. The third problem makes the analysis rather complex, as the usual assumption of single phase layers is not obeyed.

We have performed studies on a variety of Si_xGe_{1-x} structures for devices and superlattices, both on Si and Ge[17-19]. First we tested an HBT structure with a thick emitter but a constant composition x in the base[17]. Thus we dealt with two of the three problems mentioned above.

A Si_xGe_{1-x} HBT structure was grown in a dual e-gun Si MBE system. The nominal structure obtained from the growth calibration is shown in Figure 4, left-hand side. The HBT material was characterized by x-ray diffraction (XRD) and secondary ion mass spectroscopy (SIMS) in addition to ellipsometry. The XRD result shows a composition x=0.83±0.002. Using the points where the Ge signal dropped to half the peak value, the SIMS depth profile gave an emitter thickness of 590±10 nm, and a base of 85±10 nm.

NOMINAL			ELLIPSOMETRY	
2 nm	Oxide		Oxide	4.55 +/- 0.07 nm
120 nm	Si n^{++}	$2X10^{19}$ Sb	Si	594.3 +/- 0.75 nm
480 nm	Si n^{+}	$2X10^{18}$ Sb		
92.3 nm	Si_xGe_{1-x}		Si_xGe_{1-x}	88.5 +/- 0.97 nm
	Si	$1X10^{17}$ Sb	Si substrate	
	Si substrate p			
x=0.8			x=0.862 +/- 0.008	
			MSE: $2.07X10^{-3}$	

Figure 4. Nominal structure (left-hand side) and ellipsometry results (right-hand side) of an HBT sample.

Ellipsometry measurements were performed at four angles of incidence, over spectrum range was 300-780 nm, in 5 nm steps. As usual in ellipsometry, a model was assumed with the nominal structure. As doping below the high 10^{19} cm^{-3} is not observable by ellipsometry, only four parameters were assumed as variables: oxide, emitter and base thickness, and the composition x. The final ellipsometry results are the values obtained for the four variable parameters using a non-linear least squares fit to the experimental results. We used the relaxed Si_xGe_{1-x} dielectric calibration functions. The model calculations using the best fitted four parameters shows good agreement with the experiment. The values of the four parameters are given in Figure 4, right-hand side, with the corresponding 90% confidence limits. MSE is a measure of the quality of the fit[17]. The ellipsometry determined thickness for the emitter and the base are in very good agreement with both the nominal and the SIMS values. The composition x is 0.03 higher than the extremely reliable value obtained by XRD. It turns out that a coherently strained Si_xGe_{1-x} layer under a Si layer measured by ellipsometry and using relaxed Si_xGe_{1-x} calibration functions will give a value of x which is higher by 0.03 vs. the XRD value[20]. The higher than expected oxide layer was due to previous heating to 150 °C for this particular sample.

As a second step to a complete HBT structure characterization, we tested several graded layers[19], with grading from x=1 to 0.7 and to 0.5. The graded layers were uncapped and nominally 1 μm thick. Ellipsometry measurements were done in the spectral range 300-800 nm, at three angles of incidence. Again, we used the relaxed dielectric calibration functions. The graded layer was assumed to be made of n thinner layers, each one with a constant composition x, where x varied linearly from one to the value on top, x_n (x_n(nom) is the nominal composition on the top surface). We found that for n>20 the results are independent of n. Thus, by using n=30 we got a good approximation to the continuously graded layer. Results for two of the samples are shown in Table 1. The main features of the results are: 1. The Si_xGe_{1-x} layer thickness is in excellent agreement with the nominal values; 2. The oxides are thicker than expected. We believe this is a result of the surface roughness, a common occurrence in Si_xGe_{1-x} films; 3. The composition parameter x_n is too high for all samples. We believe that the reason for the high x_n values is due to two factors: 1. The surface is probably rough; 2. There is residual strain in the samples. Sample B has a larger deviation vs. sample A, and it also has possibly more strain than A. The fact that the layers were thick does not mean that they were totally relaxed. XRD of a 0.61 thick Si_xGe_{1-x} layer with x=0.8 showed only a 65%-70% relaxation[21]. Thus it is unclear whether our samples were totally relaxed. It seems that more work on a variety of graded samples is required for an accurate determination of the composition.

Table 1. Ellipsometric results for graded Si_xGe_{1-x} on Si.

Sample	d(oxide) (Angstrom)	D (Si_xGe_{1-x}) (μm)	x_n	x_n (nom)
A	44.8	1.04	0.767	0.7
B	43.0	0.97	0.587	0.5

PASSIVE COMPONENTS ON HIGH RESISTIVITY SILICON

As early as 1965, it was recognized that microstrip transmission lines on standard CMOS grade Si wafers with a resistivity, ρ, of 0.1 to 10 Ohm—cm were too lossy, and High Resistivity Silicon (HRS) wafers with $\rho > 2500$ Ohm-cm are necessary for microwave and millimeter-wave microstrip[22]. Later experiments showed that $\rho > 2500$ ohm-cm was also required for Coplanar Waveguide (CPW) transmission lines[23]. A comparison of the attenuation of CPW on GaAs and a HRS wafer is shown in Figure 5. Although the attenuation of the Si line is greater the GaAs line by approximately 0.2 dB/cm, the effective dielectric constant of the Si line is lower than the GaAs line by approximately 7 %. Thus, if the attenuation is plotted in the more useful units of dB per wavelength, the attenuation of the Si line is only 0.1 dB/λ greater than the GaAs line as shown in Figure 6.

Besides microwave transmission lines on Si having a comparable attenuation to similar lines on GaAs, passive components and discontinuities also have similar characteristics. For example, consider the CPW short circuit terminated series stub that is often used as a series inductor or as a stop band filter element[24]. The characteristics of the stub fabricated on HRS and GaAs are shown in Figure 7. Note that except for a small shift in the resonant frequency due to the slightly lower relative permittivity of Si compared to GaAs, the characteristics are identical. Furthermore, if the loss factor, $1-|s_{11}|^2-|s_{21}|^2$, is calculated from Figure 7, it is seen that circuits fabricated on HRS do not suffer a degradation in performance when compared to circuits on GaAs.

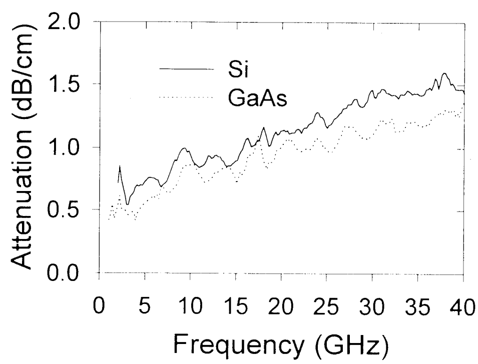

Figure 5. Attenuation per length of CPW line with S = W = 50 μm on GaAs and ρ > 2500 Ohm-cm Si.

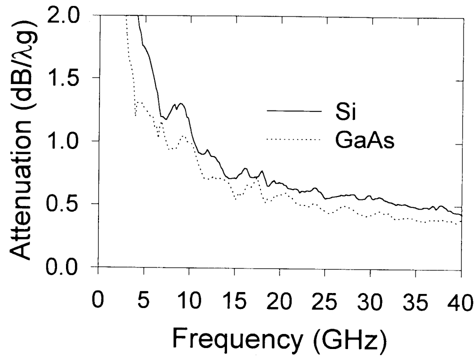

Figure 6. Attenuation per guided wavelength of CPW line with S = W = 50 μm on GaAs and $\rho > 2500$ Ohm-cm Si.

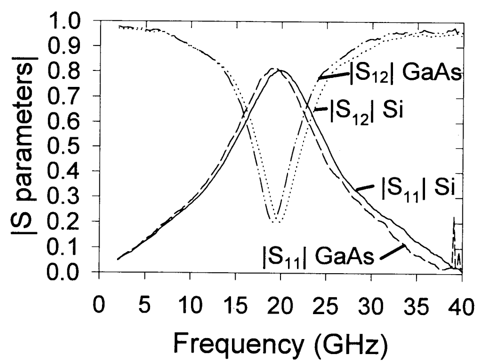

Figure 7. Magnitude of S-parameters of CPW short circuit series stub fabricated on GaAs and HRS.

DISCUSSION

The excellent results published in the literature and within this paper provide encouragement that Si MMICs are not only possible, but they can provide the performance required for the emerging commercial markets with further development. Although Si MMICs are used in nearly every RF system below 2 GHz, there has been very little development above 20 GHz. Furthermore, the integration of microwave and digital circuitry has not occurred.

To address these issues, the University of Michigan and NASA Lewis Research Center are working to develop SiGe HBTs for microwave applications utilizing the LT-Si buffer layer that was developed. In addition, full characterization of Si as a microwave substrate and methods to reduce the attenuation of transmission lines on Si by utilizing micromachining technology are being performed. These efforts will be demonstrated in a series of Ka-band Si MMICs.

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