High electron mobility in SiGe/Si n-MODFET structures on sapphire substrates

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For the first time, SiGe/Si n-Modulation Doped Field Effect Transistors (n-MODFET) structures have been grown on sapphire substrates. Room temperature electron mobility value of 1271 cm^2/V-sec at an electron carrier density (n_e) of $1.6x10^{12}$ cm^{-2} was obtained. At 250 mK, the mobility increases to 13,313 cm^2/V-sec (n_e=$1.33x10^{12}$ cm^{-2}) and Shubnikov-de Haas oscillations appear, showing excellent confinement of the two-dimensional electron gas.

Introduction: Development of SiGe/Si-based circuitry on electrically insulating sapphire substrates is being pursued for K-band (12 – 18 GHz) frequency and higher applications that require high levels of digital and analog integration on a single substrate, such as transceiver modules for phased array antennas. The device structure presented in this paper capitalizes on advances made in SiGe/Si n-type modulation doped field effect transistor (n-MODFET) growth on Si substrates [1]. Substitution of the poorly insulating Si substrate with sapphire provides several benefits. At the transistor level, the advantages of the sapphire substrate are analagous to those obtained using Si-on-insulator technology (SOI). These advantages include reduced parasitic reactances caused by coupling of the transistor terminals to the body of the substrate, which enables low-power and high-speed operation [2]. At the device integration level, the insulating substrate is superior to SOI as it enables higher Q inductors, lower-loss RF transmission lines, and improved isolation between devices located on a common substrate [3].

For n-MODFET structures, the presence of Shubnikov-de Haas oscillations at cryogenic temperatures and Hall measurements over a wide range of temperatures have been used to verify that the structures display two-dimensional electron gas behavior, and to quantify the quality of the structure. The existence of Shubnikov-de Haas oscillations in SiGe/Si n-MODFET structures on substrates other than directly onto Si is rare; for example, Paul et al. [4] reported Shubnikov-de Haas oscillations in n-MODFET SiGe/Si structures grown on bonded SOI substrates. Koester et al. reported p-MODFET structures on sapphire with room temperature hole mobilities of 800 cm^2/V-sec; low temperature data was not presented [5]. To the best of our knowledge, no one has reported n-MODFET behavior in SiGe/Si structures on sapphire substrates, nor the existence of Shubnikov-de Haas oscillations in SiGe/Si MODFETs (either n- or p-type) deposited on sapphire substrates.

Experimental: SiGe/Si n-MODFET growth on r-plane sapphire substrates was accomplished using a multi-step process. First, commercial r-plane sapphire substrates with 270 nm thick Si films were obtained from St. Gobain Crystals, Inc. The crystalline quality of the Si films was improved using a solid phase epitaxy and regrowth process. In our study, Si ions were implanted into the Si films at a dose of $2x10^{15}$ cm^{-2}, at a beam energy of 180 keV. The samples were annealed for three hours at 1100 °C in flowing N_2, followed by an eight hour O_2 anneal, also at 1100 °C. The oxide was chemically etched to achieve a 100 nm thick Si layer. The SiGe buffer layer, virtual substrate, and n-MODFET structures were deposited using molecular beam epitaxy (MBE). A schematic drawing of the various layers is shown in figure 1. Antimony (Sb) was incorporated into the donor layer via a delta-doping approach using an Sb_4 source, immediately following growth of the top $Si_{0.7}Ge_{0.3}$ spacer layer. Both the top spacer layer and delta-doped Sb layer depositions were performed at a substrate temperature of 500 °C. Next, the substrate temperature was decreased to 200 °C for

seven seconds and a thin (~ 1 nm) $Si_{0.7}Ge_{0.3}$ layer deposited, so as to minimize Sb segregation. The substrate temperature was increased to 500 °C and the remaining 9 nm of the donor layer and 5 nm Si cap layer deposited. Hall effect measurements to measure electron mobility and carrier concentration were made at room temperature and 250 mK. Shubnikov-de Haas data was taken at 250 mK.

Results: Table 1 summarizes the Hall mobility results. The high room temperature mobility (1271 cm^2/V-sec), coupled with the reasonably high carrier density of 1.6×10^{12} cm^{-2} and short surface-to-channel distance (20 nm) makes these structures attractive for high frequency system-on-a-chip applications. Although Si films deposited directly on sapphire are compressively stressed [6], the high mobility demonstrated by the n-MODFET devices of this study indicate that the buffer layer and virtual substrate were capable of supporting growth of the high quality, tensile-strained Si channels necessary for 2DEG formation and high electron mobility. For comparison, the bulk mobilities of Si and $Si_{0.7}Ge_{0.3}$, doped to 1×10^{18} cm^{-3}, are less than 300 cm^2/V-sec [7]. Table 1 also demonstrates that the electron density changes little as the temperature is lowered, indicating excellent carrier confinement at all temperatures.

The existence of a two-dimensional electron gas is demonstrated by the presence of Shubnikov-de Haas oscillations in figure 2. Longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistances were measured at 250 mK as a function of magnetic field intensity, for fields up to 9 Tesla (T). As the magnetic field is increased to ~ 3.5 T, the oscillatory ρ_{xx} behavior and linearly increasing ρ_{xy} indicates a two-dimensional electron gas with doubly degenerate Landau levels. An electron carrier density of 1.33×10^{12} cm^{-2} was determined from the slope of the ρ_{xy} vs. magnetic field data. Using as a reference that the $v = 1$ filling factor corresponds to $\rho_{xy} = h/e^2$ (i.e. 25.8 kΩ), and that ρ_{xy} at lower

magnetic field intensities and thus higher filling factors is given by 25.8/v, we assigned values of v=10 and 8 to the peak minima occurring at magnetic fields of 5.4, and 6.5 T, respectively. At 5.4 T, the ρ_{xx} double peak and even order of the filling factor indicate spin splitting. The well-defined ρ_{xy} plateau and ρ_{xx} minimum at ~ 6.5 T marks a region of zero dissipation, where the Fermi energy is located between Landau levels.

Conclusions: We report, for the first time, SiGe/Si n-MODFET structures on sapphire substrates. The electron mobility was 1271 and 13,313 cm^2/V-sec at room temperature and 250 mK, respectively. The presence of Shubnikov-de Haas oscillations confirms that the structure operates as a two-dimensional electron gas. The constancy of carrier concentration from room temperature to cryogenic temperatures indicates the carrier confinement is excellent even at room temperature. These results are encouraging for the development of integrated system-on-a-chip transceivers on sapphire substrates.

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Figure and table captions:

Figure 1. Schematic diagram of buffer layer, virtual substrate, and n-modulation doped field effect transistor structure on r-plane sapphire substrate.

Table 1. Summary of electron mobility, electron concentration, and sheet resistance at selected temperatures.

Figure 2. Longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistivity as a function of magnetic field (T). Data taken at 250 mK.
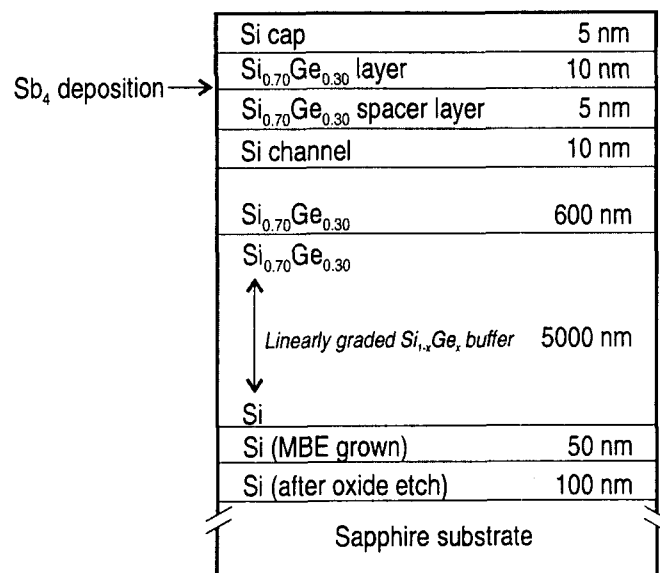
Figure 1

Si cap	5 nm
Si$_{0.70}$Ge$_{0.30}$ layer	10 nm
Si$_{0.70}$Ge$_{0.30}$ spacer layer	5 nm
Si channel	10 nm
Si$_{0.70}$Ge$_{0.30}$	600 nm
Si$_{0.70}$Ge$_{0.30}$ ↕ *Linearly graded Si$_{1-x}$Ge$_x$ buffer* Si	5000 nm
Si (MBE grown)	50 nm
Si (after oxide etch)	100 nm
Sapphire substrate	

Sb$_4$ deposition →

Table 1

Temperature (K)	Electron Concentration ($\times 10^{12}$ cm^{-2})	Hall Mobility (cm^2/V-sec)	Sheet Resistance (Ω/sq.)
300	1.6	1271	3073
0.250	1.33	13,313	352

Figure 2