High quality Ge thin film grown by ultrahigh vacuum chemical vapor deposition on GaAs substrate

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High-quality epitaxial Ge films were grown on GaAs substrates by ultrahigh vacuum chemical vapor deposition. High crystallinity and smooth surface were observed for these films by x-ray diffraction, transmission electron microscopy, and atomic force microscopy. Direct band gap emission (1550 nm) from this structure was detected by photoluminescence. Valence band offset of 0.16 eV at the Ge/GaAs interface was measured by x-ray photoelectron spectroscopy. N-type arsenic self-doping of $10^{18}/\text{cm}^{-3}$ in the grown Ge layers was determined using electrochemical capacitance voltage measurement. This structure can be used to fabricate p-channel metal-oxide-semiconductor field-effect transistor for the integration of Ge p-channel device with GaAs n-channel electronic device. © *2011 American Institute of Physics*. [doi:10.1063/1.3580605]

In the past several decades, there has been a steady step-up of device performance along with the continued reduction in device feature sizes for silicon devices. Furthermore, for small feature size silicon devices, additional gaining in carrier mobility can be achieved by applying a strain to the channel material.[1] In contrast to these Si devices, high-speed devices made from III–V materials are characterized with a high electron mobility but still suffer from low hole mobility. Therefore, it is still a challenge to find a p-channel material with high hole mobility.

The epitaxial Ge layer on GaAs substrate as the p-channel material for complementary III–V CMOS logic is studied in this letter. In the past few years, devices with Ge channel material on Si substrate have been fabricated, and a higher p-channel hole mobility has been reported.[2] The increasing interest to pursue this Ge/GaAs approach is due to the following reasons: (1) Ge has a much higher bulk hole mobility ($\mu_h = 1900\ \text{cm}^2/\text{V s}$) as compared to GaAs ($\mu_h = 400\ \text{cm}^2/\text{V s}$), (2) the Ge/GaAs interface has a very small lattice mismatch (~0.08%), therefore thicker Ge films can be grown on GaAs substrates with very low threading dislocation density, and (3) the narrower band gap of Ge ($E_g = 0.66$ eV) lies within a wider band gap of GaAs (1.42 eV), resulting in a good confinement of carriers in the Ge layer.[3]

In this work, high-quality epitaxial Ge films were deposited on GaAs by ultrahigh vacuum chemical vapor deposition (UHVCVD). In-depth characterizations of film structure, optical and electrical properties, and doping conditions were carried out using methods of x-ray diffraction (XRD), cross-sectional transmission electron microscopy (TEM), atomic force microscopy (AFM), photoluminescence (PL), x-ray photoelectron spectroscopy (XPS), and electrochemical capacitance voltage (ECV) profiling. The purpose of this study is to evaluate Ge film on GaAs for potential Ge/GaAs p-channel electronic devices with high hole mobility for future integration with Si technology.

Epiready GaAs (100) wafers were used as substrates for Ge deposition. Ge deposition was carried out in an UHVCVD system using GeH_4 as Ge source. Before deposition, the as-received GaAs wafer was loaded into the load-lock chamber without any precleaning step. After the pressure of load-lock reached 2×10^{-6} Torr, the wafer was then transferred into the deposition chamber. The wafer then went through a prebake step and the native oxide (As_2O_3 and Ga_2O_3) on the surface were removed in this step. Due to the sensitive nature of GaAs substrate surface, the prebake time without arsenic overpressure was controlled carefully to prevent the decomposition of GaAs. The GaAs substrate was annealed at 600 °C for 2 min prior to GeH_4 flow. The GeH_4 flow was fixed at 10 SCCM (SCCM denotes cubic centimeter per minute at STP), the pressure was controlled at 20 mTorr, and deposition time was varied to deposit undoped Ge films to the thicknesses of 200 nm, 450 nm, and 2.75 μm.

The structural and crystalline qualities of the films were analyzed by high-resolution XRD (HRXRD) and cross-sectional TEM. The surface roughness was determined by AFM. PL measurement was used to determine the emission and the band gap of the material, the ECV profiler was used to determine the doping type and background concentration. XPS was used to determine the valence band offset (ΔE_v) between the Ge film and the GaAs substrate.

The 200 nm thick Ge film deposited at 600 °C on GaAs substrate was used for the HRXRD measurement using a Bede D1 XRD system. The scanned result is shown in Fig. 1, in which the HRXRD result is in black line and the simulated curve is in gray line, with the GaAs substrate peak at zero. The angle between the peaks of the Ge film and the GaAs

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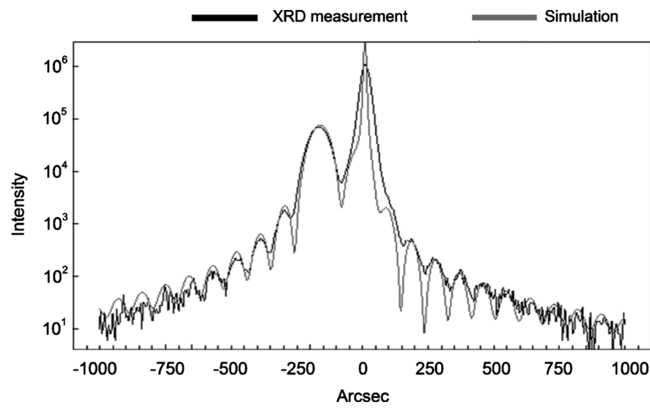

FIG. 1. XRD measurement of 200 nm Ge film on GaAs substrate. The fringes on both sides imply a sharp Ge/GaAs interface.

substrate is less than 200 arc sec. The HRXRD result and the simulated curve match closely with each other. The appearance of fringes on both sides of Ge and GaAs peaks implies a parallel and very sharp interface existed in this heterojunction structure.[2] AFM measurement of the same structure shows that the root mean square roughness (rms) was only 0.132 nm and the mean surface roughness (Ra) was about 0.104 nm. All these indicate that the Ge film grown on GaAs substrate was very uniform and can be used for the fabrication of metal-oxide-semiconductor field-effect transistor (MOSFET) or p-channel quantum well devices.

The crystalline quality of thicker Ge film was further characterized by cross-sectional TEM. Figure 2 is a cross-sectional TEM micrograph of 2.75 μm thick Ge film deposited on GaAs substrate grown at 600 °C. A few misfit dislocations are detected at the interface, but there is no appearance of any threading dislocation, which is expected. The lattice mismatch between these two materials is extremely small, which is 0.08% at room temperature and about 0.1% at growth temperature. The distance between two misfit dislocations is about 400 nm. Since the lattice constants of Ge and GaAs are 5.64 613 Å and 5.65 33 Å, respectively, therefore at the interface there are 708 lattices of Ge to match 707 lattices of GaAs at the interface. This means that for every 400 nm, an atom from the GaAs lattice is missing

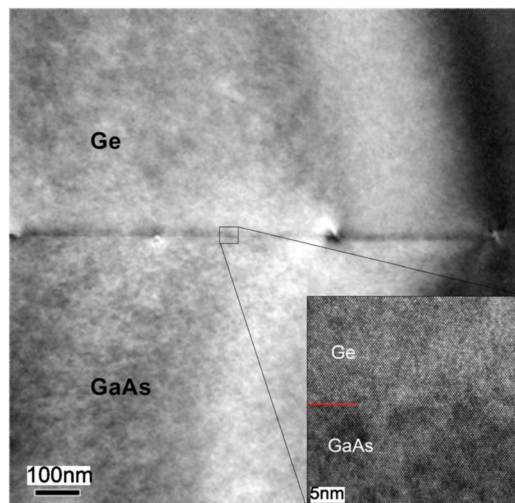

FIG. 2. (Color online) Cross-sectional TEM image of Ge on GaAs. A few misfit dislocations are seen at the interface but no threading dislocation is detected. The inset is the high resolution TEM.

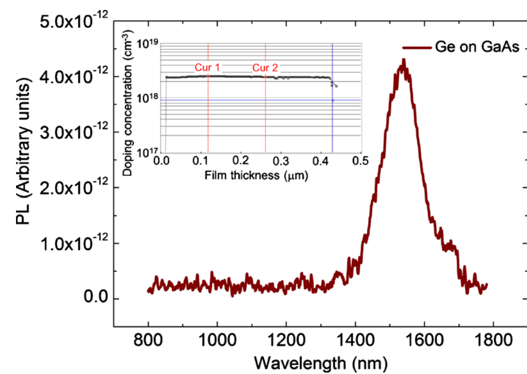

FIG. 3. (Color online) Room temperature PL infrared emission from the structure of 200 nm Ge film on GaAs substrate. The direct band gap emission occurs at 1550 nm with energy of 0.8 eV. The ECV data shows that the Ge film is n-type, and the donor concentration is about $2.49\times10^{18}/\mathrm{cm}^3$.

to form the string of one misfit dislocation. The high resolution TEM graph (the inset of Fig. 2) shows very good interface quality between Ge and GaAs.

Recently, a direct band gap emission has been observed with the structure of Ge on Si.[4–6] To obtain this emission, it requires the application of a tensile strain of under 2% to the Ge film,[7,8] a high pumping level, high temperature, and a n-type doping of Ge to compensate the 0.136 eV difference in energy between Γ and L valleys.[9] In one report, in order to increase the electron fraction of Γ valley and to move the Fermi level upwards,[6] the pump power was raised to 360 mW at room temperature. The direct radiative transition rate is about 1600 times that of the indirect transition at high power excitation.[10] The PL spectrum of Ge on GaAs is shown in Fig. 3. This is a room temperature PL infrared emission with 671 nm incident. The PL peak at 1550 nm, corresponding to an energy of 0.8 eV, reveals that the electrons in L valley recombine with holes in the valence band, the direct band gap emission occurs in the 200 nm Ge film on GaAs substrate.

In order to understand the mechanism of PL emission from the Ge sample, a Ge film with 450 nm in thickness was prepared for accurate ECV measurement to determine the type of Ge film. The result is shown in the inset of Fig. 3. The Ge film is n-type with a donor concentration of 2.49 $\times10^{18}/\mathrm{cm}^3$.

The reason that the direct band emission of Ge on GaAs substrate can be detected is probably related to the high quality of epitaxial Ge film on GaAs and the unexpected n-type doping. By filling $2.49\times10^{18}/\mathrm{cm}^3$ electrons into L valley, the energy difference between Γ valley and L valley can be compensated mostly. The band gap of L valley and the band gap of Γ valley becomes almost the same because the electrons filled the Γ valley, and some electrons injected and existed in the Γ valley. The electrons in the Γ valley recombine with holes, emitting light of direct transition at 1550 nm. The theory mentioned above is discussed in pervious study.[9] The arsenic donor was from the memory doping in the chamber which was caused by the decomposition of GaAs. The memory doping was confirmed by the horizontal profile of the donor concentration in ECV curve. This n-type Ge film can be used for the fabrication of the p-channel MOSFET, the advantage is that a Ge p-channel device can be processed adjacent to a GaAs n-channel device in a simple integration process.

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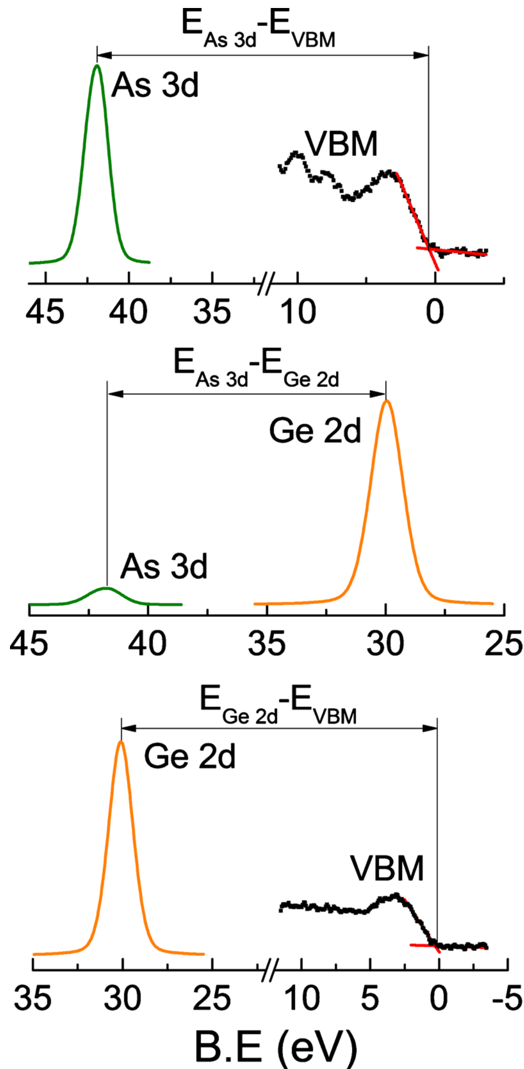

FIG. 4. (Color online) XPS spectra of (1) As $3d$ core level ($E_{As\ 3d}$) and VBM (E_{VBM}) of GaAs film, (2) As $3d$ core level ($E_{As\ 3d}$) and Ge $2d$ core level ($E_{Ge\ 2d}$) at Ge/GaAs interface, and (3) Ge $2d$ core level ($E_{Ge\ 2d}$) and VBM (E_{VBM}) of Ge film.

The valence band offset (ΔEv) at the Ge/GaAs interface was determined from XPS measurements of the binding energy of core level and valence band maximum (VBM). The valence band offset value can be determined with the equation by Kraut *et al.*,[11]

$$\Delta E_V = (E_{As\ 3d} - E_{VBM}) - (E_{Ge\ 2d} - E_{VBM}) + (E_{Ge\ 2d} - E_{As\ 3d}).$$

ΔE_V is determined from the difference between As $3d$ core level ($E_{As\ 3d}$) and VBM (E_{VBM}) of GaAs film, As $3d$ core level ($E_{As\ 3d}$) and Ge $2d$ core level ($E_{Ge\ 2d}$) at Ge/GaAs interface, Ge $2d$ core level ($E_{Ge\ 2d}$) and VBM (E_{VBM}) of Ge film. In order to measure the binding energy and VBM, XPS measurements were carried out on two Ge films with thicknesses of 10 nm and 100 nm, respectively, grown on GaAs substrates together with one piece of pure GaAs wafer. Figure 4 shows the XPS spectra of As $3d$ core level ($E_{As\ 3d}$) and VBM (E_{VBM}) of GaAs film, As $3d$ core level ($E_{As\ 3d}$) and Ge $2d$ core level ($E_{Ge\ 2d}$) at Ge/GaAs interface, Ge $2d$ core level ($E_{Ge\ 2d}$) and VBM (E_{VBM}) of Ge film. The values of $E_{As\ 3d}-E_{VBM}$, $E_{Ge\ 2d}-E_{VBM}$, and $E_{Ge\ 2d}-E_{As\ 3d}$ are 41.25 eV, 29.81 eV, and −11.6 eV, respectively. The value of valence band offset (ΔEv) at the Ge/GaAs interface is 0.16 eV which is consistent with the theoretical value proposed by Kraut *et al.*[11] From these measurements, it is further proved that the Ge/GaAs structure can be used for heterojunction devices such as p-channel quantum well devices.

High quality Ge films were grown on GaAs substrate by UHVCVD, as confirmed by XRD and TEM. The film thickness was uniform with smooth interface, as indicated by AFM and HRXRD. A direct band gap emission (1550 nm) of Ge epitaxial layer/GaAs substrate was detected by PL and ECV measurement showed the grown Ge layers were n-type doped with arsenic self-doping concentration of $10^{18}/\mathrm{cm}^{-3}$. The valence band offset (ΔEv) at the Ge/GaAs interface is 0.16 eV which is consistent with the theoretical value. This structure studied is useful for the future integration of Ge p-channel and GaAs n-channel electronic devices on Si template.

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