Thin Solid Films 321 (1998) 51–54

Effective mass measurement in two-dimensional hole gas in strained $Si_{1-x-y}Ge_xC_y$/ Si(100) modulation doped heterostructures

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Abstract

A two-dimensional hole gas in the $Si_{1-x-y}Ge_xC_y$ channel on a Si(100) substrate has been demonstrated at temperatures from 0.3 to 300 K. The hole mobility decreases as more C is added. The hole effective mass has also been measured based on the analysis of the temperature dependence of Shubnikov–de Haas oscillations. It is found that the addition of C, up to 0.6%, does not change the effective mass of holes in $Si_{1-x}Ge_x$. It suggests that the valence band structure of $Si_{1-x-y}Ge_xC_y$ is similar to that of $Si_{1-x}Ge_x$. © 1998 Elsevier Science S.A. All rights reserved

Keywords: Mass measurement; 2D hole gas; Si(100)

1. Introduction

Strained $Si_{1-x-y}Ge_xC_y$ alloys on Si(100) substrates have attracted strong interest because the addition of substitutional C into $Si_{1-x}Ge_x$ reduces the strain caused by Ge atoms [1–3]. Photoluminescence studies of $Si_{1-x-y}Ge_xC_y$ sandwiched by Si layers [2,3] and electrical measurements on the $Si_{1-x-y}Ge_xC_y$-based bipolar transistors [4] indicate that the initial incorporation of substitutional C increases the bandgap of $Si_{1-x-y}Ge_xC_y$ pseudomorphically grown on Si(100) substrate, with the bandgap increasing by 21–25 meV when 1% C is added. The rate of bandgap increase, however, is not as rapid as that in the case where the strain in the $Si_{1-x}Ge_x$ alloys on Si is reduced by removing some Ge fraction [3]. This implies that, for a desired bandgap, a thicker $Si_{1-x-y}Ge_xC_y$ than $Si_{1-x}Ge_x$ layer may be grown without generation of misfit dislocations.

Given the potential of $Si_{1-x-y}Ge_xC_y$/Si, it is imperative to know its carrier transport properties and compare them with those in the $Si_{1-x}Ge_x$/Si system. Two-dimensional modulation doped hole gases can in principle be fabricated since the band offset at the $Si_{1-x-y}Ge_xC_y$ /Si interface is predominately in the valence band [5]. To date, however, there are very few reports on the transport properties of holes in the Si_{1-x-y} Ge_xC_y/Si interface and reports of transport properties are limited to the temperature range of 77–300 K [6]. In this paper, we report a transport study of two-dimensional hole gas in a strained $Si_{1-x-y}Ge_xC_y$/ Si(100) modulation doped structure from room temperature to 0.3 K. We also report the effective mass measurement of holes in $Si_{1-x-y}Ge_xC_y$/Si by studying the temperature dependence of Shubnikov–de Haas (SdH) oscillations from 0.3 to 4 K.

2. Experimental

The samples used in this study were grown by rapid thermal chemical vapor deposition (RTCVD) on lightly doped n-type Si(100) wafers. A 1 μm undoped Si buffer was first deposited at 1000°C, followed by the growth of 180 Å undoped $Si_{1-x-y}Ge_xC_y$ at 575°C. A 50 Å undoped Si spacer was then grown at 700°C, with the subsequent growth of a 50 Å boron-doped p-type Si layer (doping~$2 \times 10^{18}/cm^3$) to supply holes to the $Si_{1-x-y}Ge_xC_y$ channels. After continuing the growth with 600 Å undoped Si, a 100 Å p-type Si ($1 \times 10^{18}/cm^3$) was finally grown as a cap layer. The doped Si cap layer is used to shield the $Si_{1-x-y}Ge_xC_y$ channel from the effects of surface states. The doping in the cap and supply layer was chosen to avoid the formation of

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PII S0040-6090(98)00442-8

metallic layers which would result in hole conducting channels even at low temperatures. Dichlorosilane ($Si_2H_2C_{12}$), germane (GeH_4) and methylsilane ($SiCH_6$) were used as the precursors of Si, Ge and C, respectively. The flow rates were 26 sccm for dichlorosilane, 1 sccm for germane and 0–0.1 sccm for methylsilane, in a 3 l/min H_2 carrier and the growth pressure was 6 torr. The resulting germanium content in the $Si_{1-x-y}Ge_xC_y$ alloys was fixed at 24% and the C level ranged from 0 to 0.6%. The growth temperature was low and the C content was chosen to be below 1.0% to ensure 100% C substitutionality. Since samples grown under similar growth conditions previously indicated that C is close to 100% substitutional for C level up to 1%, we kept C content below 1% in this experiment to exclude effects caused by interstitial C.

A lithographically defined Hall Bar structure was used for the Hall measurements as well as the SdH measurements. To fabricate a Hall Bar structure, a Hall geometry was first patterned and then dry-etched in CF_4/O_2 ambient. A 1000 Å thick Å1 was then thermally evaporated and patterned for metal contacts. The contact to the hole gas in the $Si_{1-x-y}Ge_xC_y$ channel was obtained by annealing at 300°C.

3. Results

Fig. 1 shows the mobility and carrier density of two-dimensional (2D) hole gas in the $Si_{1-x-y}Ge_xC_y$ channel from room temperature to 10 K. The initial decreasing and eventual saturation of hole density indicate the freeze-out of parallel conduction paths and the gradual transfer of holes to the $Si_{1-x-y}Ge_xC_y$ channels as temperature is decreased. In contrast, the hole mobility increases with decreasing temperature. This is evidence of the formation of 2D hole gas in the $Si_{1-x-y}Ge_xC_y$ channels. The hole mobility at low temperatures decreases as C is incorporated. For example, at 10 K the mobility with no C is 1800 cm^2/V s compared to 1500 and 800 cm^2/V s with C levels of 0.3 and 0.6%, respectively. It is not clear at this point if the decrease in hole mobility is due to enhanced alloy scattering with the addition of C, or other factors, such as increased interface roughness or C-related defects. The carrier density saturates at ~$10^{12}/cm^2$ at low temperatures, suggesting a complete hole transfer, as intended, from Si dopant layer to $Si_{1-x-y}Ge_xC_y$ channels. The variations in the carrier density may be due to imperfect doping control during growth and is not thought to result from a change in the valence band.

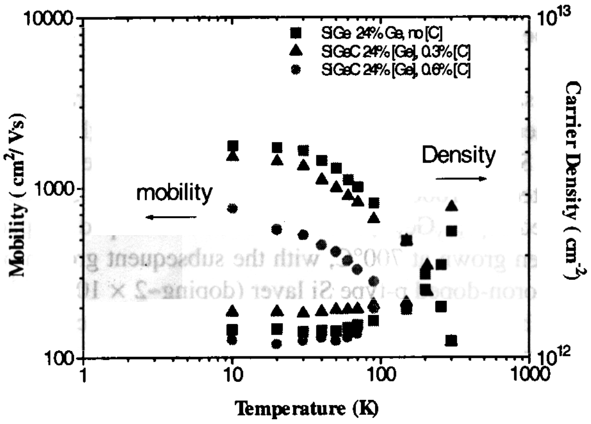


Fig. 1. Hole density and mobility as a function of temperature for Si/$Si_{1-x-y}Ge_xC_y$ modulation doped heterostructures.

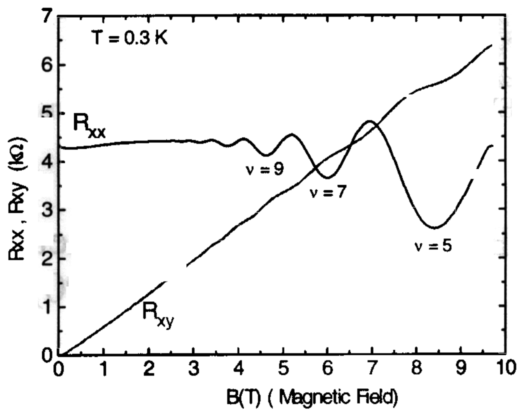


Fig. 2. SdH oscillations of 2D hole gas in the $Si_{0.754}Ge_{0.24}C_{0.006}$ channel at 0.3 K.

To measure the hole effective mass, samples were placed in a ^3He system for the observation of SdH oscillations in the magnetotransport measurements. Fig. 2 shows the SdH oscillations of $Si_{1-x-y}Ge_xC_y$ with 0.6% C as a function of magnetic field up to 10 T. The oscillation begins at around 3 T and becomes more pronounced at higher magnetic fields, indicating that the oscillation is moving toward the quantum Hall regime. At the same time, transverse resistance (R_{xy}) reveals a few weak quantum Hall plateaux. It is noted that only odd filling factors are resolved which could be due to a rather large g-factor, causing the Zeeman splitting to match the Landau level splitting [7]. Since the SdH oscillation is periodic in the reciprocal magnetic field, one can determine the carrier density from the periodicity. The obtained number from this method is 9.8 × $10^{11}/cm^2$. From the slope of R_{xy} at low magnetic fields, one finds carrier density

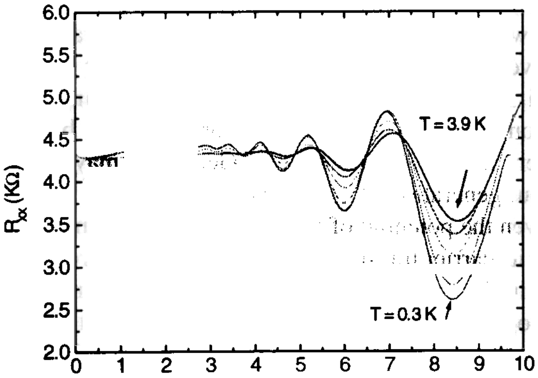


Fig. 3. SdH oscillations of 2D hole gas in the $Si_{0.754}Ge_{0.24}C_{0.006}$ channel at various temperatures.

of $9.4 \times 10^{11}/\text{cm}^2$. By combining R_{xx} and R_{xy} one finds the hole mobility to be ~2500 cm²/V s at 0.3 K for $Si_{1-x-y}Ge_xC_y$ with 0.6%.

The hole effective mass in the $Si_{1-x-y}Ge_xC_y$ channels is determined by measuring the change of SdH oscillation amplitude as a function of temperature [8–10]. The amplitude decreases with increasing temperatures as the Fermi distribution broadens at higher temperatures and leads to partial occupation of holes at higher Landau levels for holes in the higher energy tail of the Fermi function, as shown in Fig. 3. The dependence of the oscillation amplitudes on the effective mass arises from its dependence on the energy spacing of the Landau levels, which scales inversely to the effective mass change. The temperature dependence of the oscillation amplitude (A) at a given magnetic field (B) can be expressed by:

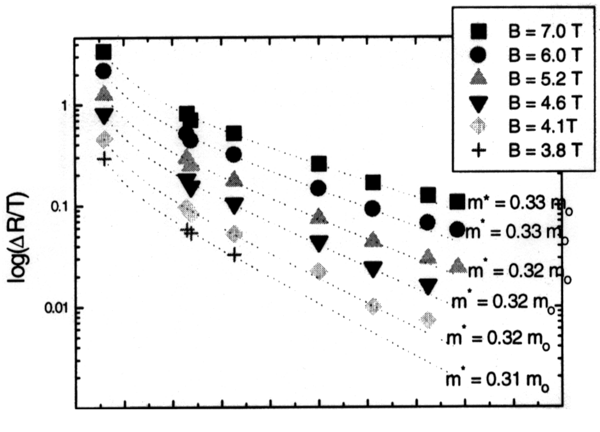
$$A \sim \frac{\xi}{\sinh(\xi)} \exp\left(-\frac{\pi}{\tau\omega_c}\right)$$

where

$$\xi = \frac{2\pi^2 \kappa_B T}{h\omega_c}, \quad \omega_c = \frac{eB}{m^*}$$

κ_B is the Boltzmann constant and τ is the quantum lifetime.

Therefore, if the change of the oscillation amplitude is plotted as a function of temperature at a given magnetic field, one can determine the effective mass by using it as an adjustable parameter to fit the experimental data. This can be repeated at each magnetic field at which there is a peak or valley of the SdH oscillation, generating effective mass as a function of magnetic field. Fig. 4 is the result of such an analysis for the sample with a C level of 0.6%. In this sample, the hole effective mass ranges from 0.31 to 0.33 m_o The fitting error in this procedure of extracting m^* from the original data of R_{xx} versus B is estimated at 0.01 m_o. The quantum lifetime we obtained in these samples is in the order of 10^{-13} s, which is close to the transport lifetime obtained at zero magnetic field. It implies that large angle scattering dominates in these samples, attributable to a significant amount of background dopants in the channels.



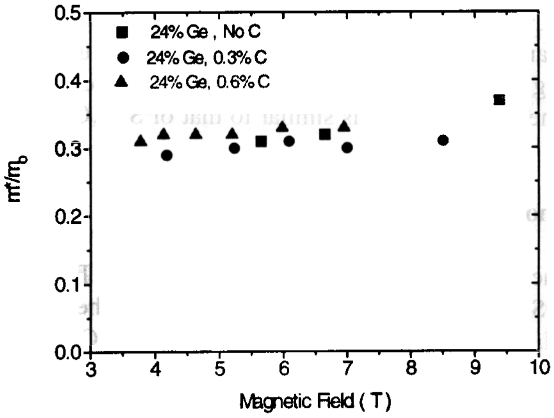


Fig. 5. Hole effective mass in $Si_{1-x}Ge_x$ and $Si_{1-x-y}Ge_xC_y$ channels measured at various fields.

Fig. 5 shows the comparison of hole effective mass in the $Si_{1-x}Ge_x$ and $Si_{1-x-y}Ge_xC_y$ channels. There is no significant change in the effective mass as C is added substitutionally up to 0.6%. It suggests that the valence band structure of compressively strained $Si_{1-x-y}Ge_xC_y$ is similar to that of $Si_{1-x}Ge_x$. It is also noted that the effective mass obtained in our samples is close to that reported by People et al. ($m^* = 0.30\ m_o$) [10] using a similar measurement technique for an MBE-grown modulation-doped heterostructure with similar Ge concentration (20%) and no C.

A calculation of the valence band structure of $Si_{1-x}Ge_x$ (with 24% Ge) shows that the energy splitting between heavy hole band (HH) and light hole band (LH) at $\kappa = 0$ is 47 meV [11]. In the sample with 0.6% C, if one considers the strain reduction due to the incorporation of substitutional C and assumes the deformation potential to be the same in $Si_{1-x-y}Ge_xC_y$ as in $Si_{1-x}Ge_x$, the HH–LH splitting in the sample is 39 meV. For the 2D hole density in this study ($1 \times 10^{12}/\text{cm}^2$), the Fermi level is 7 meV away from the top of the heavy hole band, (assuming effective mass of 0.3 m_o). This indicates that holes occupy only the very top of the heavy hole band. The effective mass obtained in this study is therefore the heavy hole effective mass and is not affected by any nonparabolicity due to interactions of HH and LH bands.

4. Conclusions

Two-dimensional hole gases in modulation doped $Si_{1-x-y}Ge_xC_y$ channels on Si(100) have been demonstrated with temperatures from 0.3 to 300 K. At low temperatures, it is found that the hole mobility decreases as more C is added to the $Si_{1-x}Ge_x$ alloys. Effective mass measurement based on the analysis of SdH oscillations as a function of temperature reveals that the heavy hole effective mass of

$Si_{1-x-y}Ge_xC_y$ is 0.32 m_0 and the effective mass remains unchanged from that in $Si_{1-x}Ge_x$ for C levels up to 0.6%. It suggests the valence band structure of compressively strained $Si_{1-x-y}Ge_xC_y$ is similar to that of $Si_{1-x}Ge_x$.

Acknowledgements

The authors would like to thank USAF Rome Lab, AFOSR and ONR for funding this research. The assistance of M. Yang in band structure calculations, C.C. Li in ^{3}He system operation and J.P. Lu for data reduction is also greatly appreciated.

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