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PIEZOELECTRIC EFFECT IN COHERENTLY STRAINED B-DOPED (001)SiGe/Si HETEROSTRUCTURES*

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We report on two methods which illustrate piezoelectric effects in the strained Si (100)Si_{1-x}/Ge_x system. The non-contact sound excitation technique has been used to reveal the conversion of a high-frequency electric field E into acoustic waves at 77 K which can also be modulated by a dc applied bias voltage (±30 V). The sample was an MBE grown modulation doped $Si_{0.88}Ge_{0.12}$/(001)Si structure with a carrier sheet density 2.0×10^{11} cm^{-2} and a 4.2 K mobility 10500 cm^2 V^{-1} s^{-1}. We deduce that the observed high-frequency electric field acoustic wave conversion is associated with a piezoelectric-like effect possibly due to ordering in the strained SiGe alloy or symmetry breaking effect near Si/SiGe interface. Further evidence is provided by the existence of a piezoelectric phonon interaction in the hot hole energy relaxation mechanism determined from high electric field Shubnikov de Haas He^3 low temperature measurements.

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At present, there is some experimental evidence for ordering of the Si and Ge atoms in the ⟨111⟩ direction [1–3] and for piezoelectric scattering of free holes at $T < 4.2$ K in $Si_{1-x}Ge_x$ strained layers grown on (001)Si substrates [4]. The direct observation of a piezoelectric effect in this strained alloy is of considerable interest, since it implies a certain ionic character, the nature of which may be sensitive to the presence of long range order in this system.

The acoustic experiments were carried out using the standard resonant pulse-on passage technique with a sapphire buffer rod (Fig. 1a). The sample was in acoustic contact with the end of the buffer rod and was aligned with the high-frequency (HF) electric field parallel to the growth axis (C). The field E

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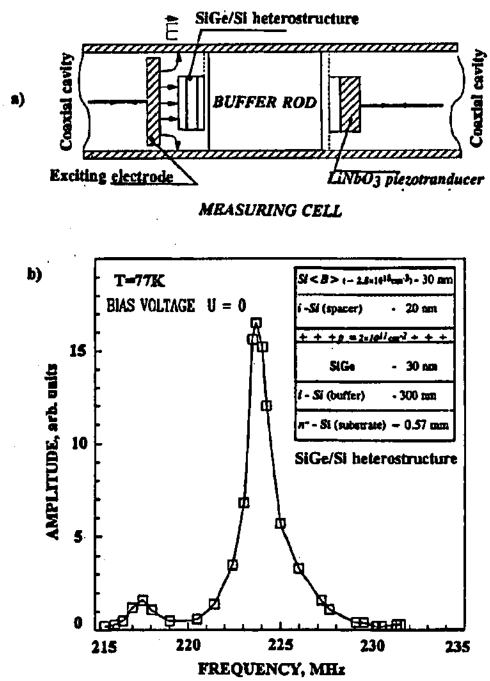

Fig. 1. (a) Experimental arrangement for hybrid acoustic–electric field measurements. (b) Amplitude–frequency dependence of the acoustic signal with a bias voltage $U = 0$ at 77 K.

was created by an electrode incorporated as a part of the coaxial cavity. The electrode was excited with a ca. 220 MHz pulse of duration ≈ 1 μs and a peak power of 0.5 W. A $LiNbO_3$ piezotransducer was located at the other end of the buffer rod to detect longitudinal acoustic modes propagating along the C-axis.

Hence, any acoustic wave generated by the field E in the sample is detected at the piezotransducer; conversely, any electric field generated by an acoustic wave is detected at the cavity. This experimental arrangement is reminiscent of a diffusion layer transducer [5].

The present sample was an MBE grown p-type modulation doped $Si_{0.88}Ge_{0.12}/Si$ heterostructure as shown in the inset of Fig. 1b. The carrier sheet density is 2.0×10^{11} cm^{-2} and the 4.2 K Hall mobility 10500 $cm^2\,V^{-1}\,s^{-1}$.

At a temperature of 77 K, the initial excitation pulse at the time $t = 0$, was followed by several (3–4) pulses, delayed by the time of flight of the longitudinal acoustic waves in the sample and buffer rod (≈ 3 μs). At room temperature however, the secondary pulses were absent.

On sweeping the frequency of the HF-generator within the bandwidth limits of the piezotransducer (≈ 15 MHz) and measuring the amplitude of the acoustic pulse, the resonant passage of the acoustic signal through the whole system is obtained as shown in Fig. 1b. It should be noted that the time of flight of an acoustic wave through the sample (of a thickness of 0.575 mm) is much smaller than the duration of the HF-pulse, i.e., we have a quasi-continuous acoustic wave in the sample. As can be seen in Fig. 1b, we observe two successive Fabry–Perot type acoustic resonances with a quality factor Q of about 160. The frequency separation Δf between successive resonances is $\Delta f = v/2d$, where v is the longitudinal sound velocity in the sample and d is the thickness of the sample. From Fig. 1b $\Delta f =$ 6.3 MHz, hence $v \approx 7.3 \times 10^5$ cm s^{-1}. Figure 2 shows the effect of applying a DC bias voltage U from the side of B-doped Si cap, over the range -30 V $< U <$ $+30$ V. As can be seen in Fig. 2 the signal is non-linear and asymmetric about $U = 0$. *Its increase with a positive voltage could be explained due to reduction in screening by free holes at the upper SiGe interface.*

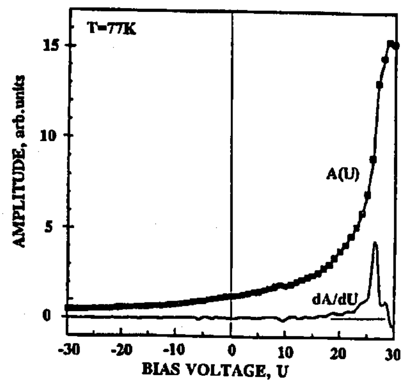

Fig. 2. Acoustic signal $A(U)$ and its first derivative $\mathrm{d}A/\mathrm{d}U$ dependence with a dc bias voltage U at frequency 224.7 MHz and $T = 77$ K.

To understand this effect, we must consider the fact that the electro-acoustic conversion is maximised when E is normal to the sample surface and that parallel application of E yields no observable effect. Since the frequency is much lower than the plasma frequency (ω_p) of the free carriers in the sample we can assume a quasi static regime. The electrostatic penetration depth, given by $\sqrt{3}v_\mathrm{F}/\omega_\mathrm{p}$ (v_F is the Fermi velocity) [6], is very much smaller than the wavelength of sound λ. Hence an electrostatic interaction with the carriers in the SiGe layer is possible.

A possible explanation of the electro–acoustic conversion is as follows: (i) the existence (due to selective boron doping) of high mobility charge carriers in the strained SiGe layer located close to the Si/SiGe interface results in the presence of internal electric fields and (ii) the symmetry-breaking Si/SiGe interface and non-centrosymmetric structure in the strained SiGe layer leads to a piezoelectric effect. Further evidence for such an effect is provided by our investigation of energy relaxation mechanisms deduced from measurements of the hot carrier Shubnikov de Haas effect carried out on the same sample. The Shubnikov de Haas oscillations were measured as a function of electric field over a carrier temperature range of 0.35–1.5 K. Following the analysis of Xie et al. [7], we deduce that the energy relaxation mechanism is dominated by a weakly screened piezoelectric phonon interaction [8, 9]. Finally we note that the Raman spectrum for this sample has additional peaks near 255 cm^{-1} and 435 cm^{-1} which have been attributed to SiGe ordering within the alloy layers [8, 10].

In conclusion, we have demonstrated the existence of a piezoelectric effect in strained $Si_{1-x}Ge_x$ using non-contact HF electro-acoustic conversion measurements. Future evidence is provided by the observation of a piezoelectric–phonon interaction as the dominant hot hole energy relaxation mechanism deduced from the high field measurements of the Shubnikov de Haas effect.

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