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New device applications of SiGe heterostructures

Shiraki Yasuhiro
Department of Applied Physics
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

SiGe heterostructure bipolar transistors are well developed and some of them are now commercially available, while many efforts are being paid on field-effect transistors. Extremely high mobility is demonstrated both for n- and p-channel transistors, which is brought by strain effects, and new devices compatible to Si LSIs are now under development. Optical devices based on Si substrates are also extensively studied by employing SiGe heterostructures. After reviewing these device applications, the future prospect of SiGe heterostructures is discussed.

Keywords: SiGe Heteroestructures; Heterostructure bipolar transistors; Ge MOS-FETs

1. Introduction

Since advanced crystal growth techniques such as molecular beam epitaxy and ultra-high vacuum chemical vapor deposition (UHV-CVD) were well established, it has become possible to introduce hetero- and quantum-structures into silicon (Si). These structures enable us to develop advanced Si devices based on new concepts which were mainly established in the field of compound semiconductors. The frontrunner of these devices is heterostructure bipolar transistors (HBTs). The cut-off frequency ft of HBTs exceeds 300 GHz and they are now in the mass production phase. Another hopeful electronic device application is field-effect transistors (FETs), particularly based on strained silicon and modulation-doping (MOD) structures. They can provide extremely high mobility and therefore high performances, much better than conventional Si MOSFETs. The mobility of n-channel MOD structures, for instance, reaches almost one million cm2/Vs at low temperatures, while the hole mobility of strained Ge layers exceeds the mobility of bulk Ge.

Another interesting application of SiGe heterostructures is optical devices including light emitters. Although the materials are indirect band-gap semiconductors, luminescence efficiency was found to be significantly improved by introducing new quantum structures. Light emitting diodes (LEDs) and micro-cavities were fabricated to demonstrate their high potential as opto-electronic devices, particularly optical interconnection and parallel processing in VLSI circuits. Quantum cascade devices based on SiGe superlattices are another application of SiGe heterostructures and are expected to become powerful emitters in tera-Herz region. Although the lasing has not been recognized yet, efficient emission in some 10 meV range was already observed.

In this paper, these new device applications of SiGe heterostructures, particularly quantum structures, are reviewed and their future prospect is discussed.

2. Heterostructure bipolar transistors (HBTs)

Heterostructure is well recognized to be very effective to improve performances of bipolar transistors and extensive studies of SiGe heterostructure bipolar transistors (HBTs) are being conducted in these days. There are two types of transistors concerning HBTs. One is so-called “drift type transistors” where the Ge content is gradually increased from the emitter side to accelerate electrons in the base and collector regions. Since the Ge content may not be high in this type, SiGe HBTs which are now commercially available have this structure. The second type is the originally proposed one and is exploiting the band offset at the emitter-base interface to prevent hole flow from the base to the emitter and increase the cut-off frequency of transistors.

The performances of the state-of-the-art of SiGe HBTs are as follows; cut-off frequencies, ft and fmax, are 375 and 250 GHz, respectively, and noise figure is 1dB at 5 GHz, better than that of compound semiconductor HBTs. BiCMOS circuits as well as discrete HBTs are now commercially manufactured for mobile phones and optical communication by many companies. From the point of view of device processing, it is noted that carbon doping contributes to the performance improvement by suppressing diffusion of boron impurities doped in the base region.

3. FET-type electronic device applications

It is well known that the band line-up at Si/(Si)Ge hetero-interfaces is significantly modified by the strain and both type-1 and 2 line-ups appear, which makes it possible to fabricate not only n- and p-type MOSFETs but also MODFETs with modulation doping structures both for electrons and holes. Figure 1 shows the temperature dependence of Hall mobility of electrons in the modulation doping structures, that is, electrons are confined in the strained Si layers while donor impurities are doped in unstrained SiGe layers where type-2 band line-up is realized. It is well seen that the mobility enhancement is proceeding year by year and it is approaching one million cm2/Vs at low temperatures. This mobility enhancement is mainly achieved by introducing new techniques to obtain high quality relaxed SiGe buffer layers on Si substrates. Particularly, the graded buffer method [1,2] where Ge content is gradually increased from 0 just on Si substrates to a certain value is very effective to improve the crystal quality of SiGe heterostructures and it has become a standard method to fabricate relaxed SiGe buffer layers

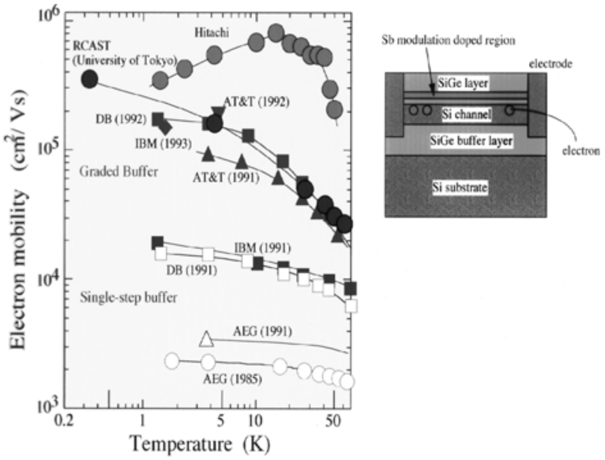

Fig. 1 Electron mobilities in SiGe heterostructures . Temperature dependence of electron mobility of various modulation doping structures (Courtesy of K. Nakagawa).

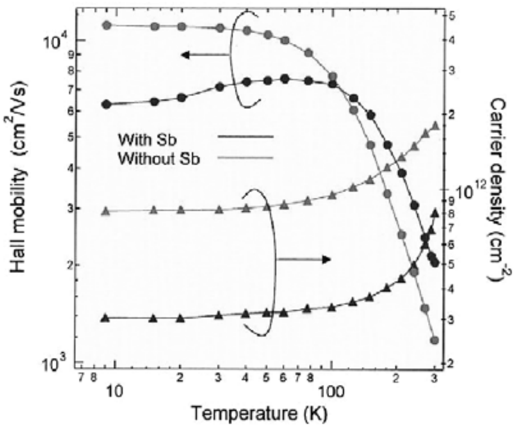

Fig. 2 Temperature dependence of mobility and carrier concentration of pure-Ge p-channel MOD structure[5].

which are sometimes called as virtual substrates. Other methods which exceed the graded buffer method have been also developed recently and high mobility is obtained both in n- and p-type channels of modulation doping structures.

Although very high mobility is expected for p-channels, however, the obtained mobility is still below the predicted value especially in the case of SiGe alloy channels, the reason for which has not been clarified yet. Very recently, extremely high hole mobility has been achieved in pure-Ge channels by two groups [3,4] one of which employs so-called low temperature (LT) buffer technique to obtain the SiGe virtual substrates where thin Si layer is grown at low temperatures before SiGe buffer layer growth.

Figure 2 shows temperature dependence of Hall hole mobility and carrier concentration of strained pure-Ge p-type channels grown on the LT buffer where low temperature growth is performed twice to obtain quite high Ge content buffer layers. It is seen that the hole mobility reaches 2,100 cm2/Vs at room temperature in the case that Sb impurities are doped to suppress parallel conduction which is commonly seen in the conventional MOD structures [5]. On the other hand, the drift mobility obtained by the mobility spectrum analysis is 2,940 cm2/Vs [4]. These values exceed the Ge bulk hole mobility and this is for the first time to experimentally show

what is anticipated by theoretical studies. The mobility enhancement comes from lightening of the effective mass of holes and suppression of inter-valley scattering in the valence bands due to the strain caused by the lattice mismatch. Actually, the effective mass of 0.09 which was much less than the Ge bulk mass of 0.19 was obtained from the Shubunikov de-Haas measurement in these samples [6].

Figures 3 and 4 show the sample structure and transistor characteristics of an MOSFET, respectively, fabricated by employing the improved MBE method based upon the above result. Parallel conduction is seen to be well suppressed in this sample and the effective mobility reaches about 3,000 cm2/Vs at room temperature as shown in Fig. 5 [5]. This result clearly demonstrates that the strained SiGe heterostructures are quite promising for high speed device applications.

From the point of view of VLSI applications, MOSFETs on strained Si, both n- and p-channels, are more attractive than MOD devices and therefore there are many studies on transistor fabrication on the strained Si.

Figure 6 shows how the performance is improved by introducing strain in Si and it is easily understood from this figure why people are interested in the strain Si. It is seen that the electron mobility experimentally obtained is enhanced in the manner almost following the expectation, however the increase of hole mobility is smaller than the expected one. Although the reason is not clarified yet, the crystal quality of p-type devices is thought to be still a problem. Since the mobility enhancement is very sensitive to the strain, the local distribution of the strain, especially in the region where carriers exist, should be precisely investigated to clarify the reason and improve the performances of p-type devices.

Since how to obtain high quality relaxed SiGe buffer layers is a critical issue and the quality of the layers obtained by the methods described above is not still satisfactory for production, there are a lot of attempts to develop better techniques. Chemical-mechanical polishing (CMP) of SiGe buffer layers before the growth of stained layers is one of promising techniques and the surface flatness almost equal to that of Si wafers is obtained and it is demonstrated that the mobility of MOD structures formed on the flat surface is enhanced due to the reduction of interface scattering [7]. Another interesting way is ion bombardment of Si substrates. Before growing SiGe buffer layers, Si substrates are ion-implanted to introduce many defects which act as nucleation centers as well as dislocation absorbers instead of the LT buffer layers [8-10]. This method is very useful for such growth methods as CVD where low temperature growth cannot be performed to decompose source gases. Only 100 nm thickness is good enough to obtain fully relaxed SiGe buffer layers with smooth surfaces, which is attracting from the point of view of production.

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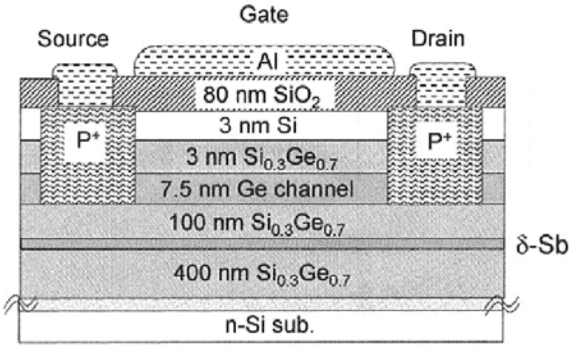

Fig. 3 Schematic of pure-Ge channel MOSFET.

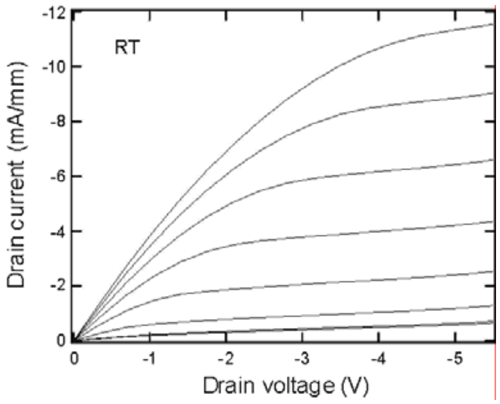

Fig. 4 I-V characteristics of pure-Ge p-type MOS FET with Sb delta-doping [5].

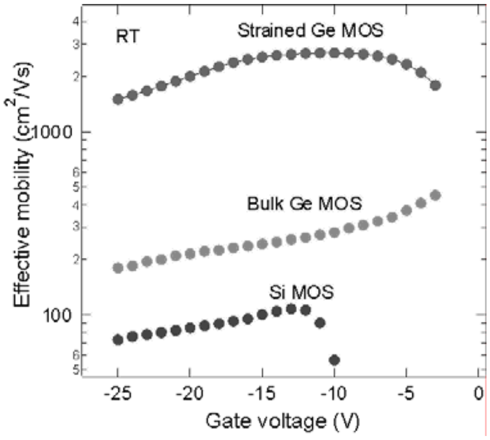

Fig. 5 Effective mobility of MOS-FETs as a function of gate voltage [5].

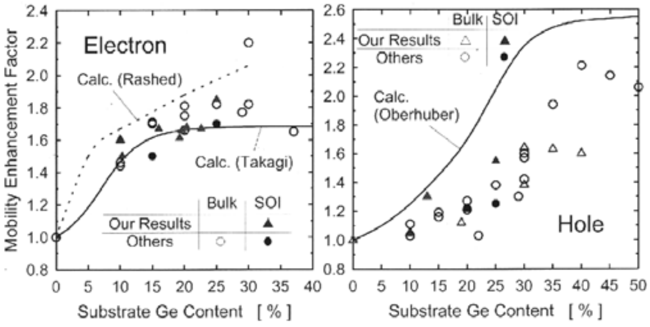

Fig. 6 Mobility enhancement factor of electrons and holes of strained Si against Ge content (Courtesy of S. Takagi).

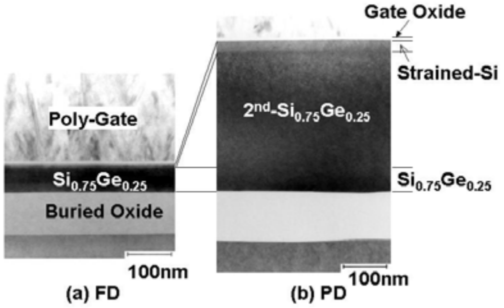

Fig. 7 TEM images of fully depleted (a) and partially depleted (b) SGOI structures [11].

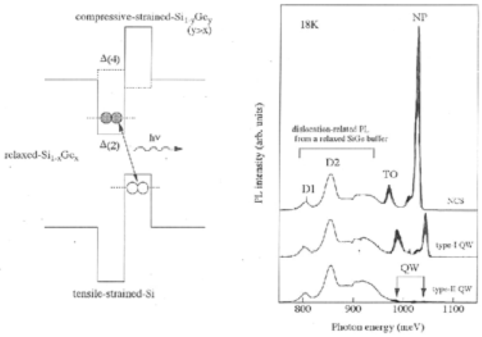

Fig. 8 Band lineup of NCS and PL spectra of the NCS along with conventional type-I and II quantum wells [13].

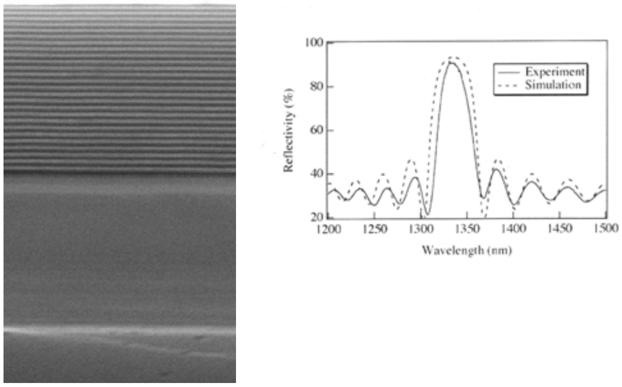

Fig. 9 TEM picture of SiGe DBR mirror and its reflectivity spectrum [14].

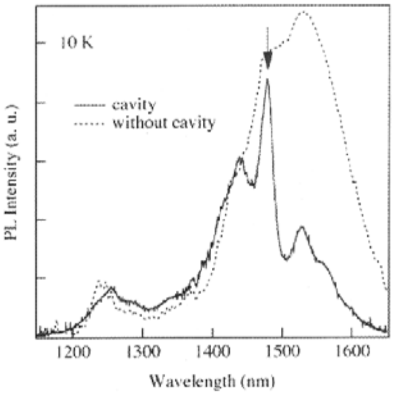

Fig. 10 PL spectra of microcavity and quantum well[15].

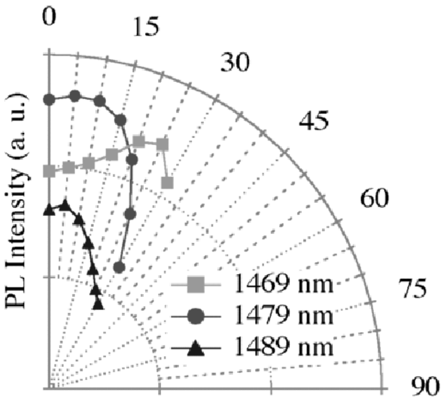

Fig. 11 Direction dependence of PL intensity.

Ultimate application of strained Si may be on silicon-on-insulator (SOI). SOI has a lot of advantages over the bulk devices such as suppression of short-channel effects and so on. Figure 7 shows TEM images of SGOI (SiGe-on-insulator) and both fully-depleted and partially-depleted SGOI structures are seen to be realized [11]. It is also demonstrated that the oscillators formed on SGOIs are much faster than those on conventional SOIs [11,12], demonstrating the high potential of SGOI structures.

4. Optical device applications

In spite of indirect band-gap nature of Si and Ge, it has been demonstrated that luminescence efficiency is significantly increased by introducing such structures as quantum wells. There are some reports on fabrication of light emitting diodes some of which emit light even at room temperature. However, since the luminescence efficiency at room temperature is still low, there are several attempts to enhance luminescence efficiency. It includes introduction of new quantum well structure such as neighboring confinement structure (NCS), quantum dots and so on.

Figure 8 shows schematic of NCS and PL spectrum of the NCS sample along with other structures [13] and it is seen that luminescence intensity, particularly no-phonon (NP) luminescence, is enhanced in the structure. In this NCS, although electrons and holes are separately confined, the band offset at the conduction band is high enough to prevent electrons from escaping from the well region compared with conventional quantum wells and therefore radiative recombination in the pair layer is largely enhanced.

Fabrication of micro-cavity structures is another approach to enhance the emission efficiency and is also now under investigation. They not only change the optical properties of materials but also enhance light emission. To realize the micro-cavity, it is necessary to fabricate distributed Bragg reflectors (DBRs) consisting of multi-layers of materials with different refractive index such as GaAs/AlAs and Si/Ge. However, since Si and Ge are lattice-mismatch system, it is hard to fabricate such thick multi-layers. To overcome this obstacle, strain-balanced structures have been recently introduced and high quality DBRs are obtained as shown in Fig. 9 [14]. In this structure, Si and SiGe layers whose thickness is 94 and 90 nm, respectively, are grown on fully relaxed SiGe buffer layers to compensate the strain. As seen in this figure, reflectivity of 90 %, which is the highest in this system, is obtained at 1.33 um. On this DBR, the active region and the upper mirror were successively grown to construct micro-cavities. The light emission was brought by using NCS structures described above. The spectrum was sharpened and the directionality of the emission was realized in this structure due to micro-cavity effects as shown in Figs. 10 and 11, respectively [15]. Moreover, the peak shift against excitation intensity which is commonly observed in indirect band-gap materials was absent in this structure. This is also thanks to the micro-cavity effects.

To enhance the temperature stability and obtain sufficient emission at room temperature, Ge dots were introduced in the emission region instead of NCS quantum wells and it was found that the activation energy of the luminescence was increased to 140 from 50 meV and the luminescence was observed at room temperature. By optimizing the structures and improve the growth, it will be possible to realize light emitting devices operating at room temperature.

Another interesting optical device application is quantum cascade lasers which have been mainly developed by using III-V compound semiconductors so far. Very recently several groups have reported on the observation of electro-luminescence (EL) in the far-infrared region from SiGe quantum cascade laser structures [16-18]. They consist of SiGe multi-layers like superlattices and the inter-subband transition in the valence band generates far-infrared emission. Figure 10 shows an example of the emission. Although this emission is not laser light yet, the laser operation will be possible by sophisticating the growth technique and the structure.

5. Future prospects

It is now widely accepted that performances of Si-VLSIs are well improved with the aid of SiGe heterostructures and a lot of work varying from material growth to device designing are being conducted in the world scale. It is therefore forecasted that SiGe heterostructures will be implemented in some important VLSI devices soon. Recently, much attention has been also paid on photonic crystals based on Si. This is because not only light emission can be well controlled but also light waveguides with high flexibility can be realized. If one can apply the photonic crystal to Si devices, waveguides for optical interconnection may be realized on Si-VLSIs. Moreover, by combining VLSIs and sophisticated Si new devices with optical functions, multi-processing of signals which is highly desired for such devices as image processors can be realized based on Si. In this case, SiGe heterostructures

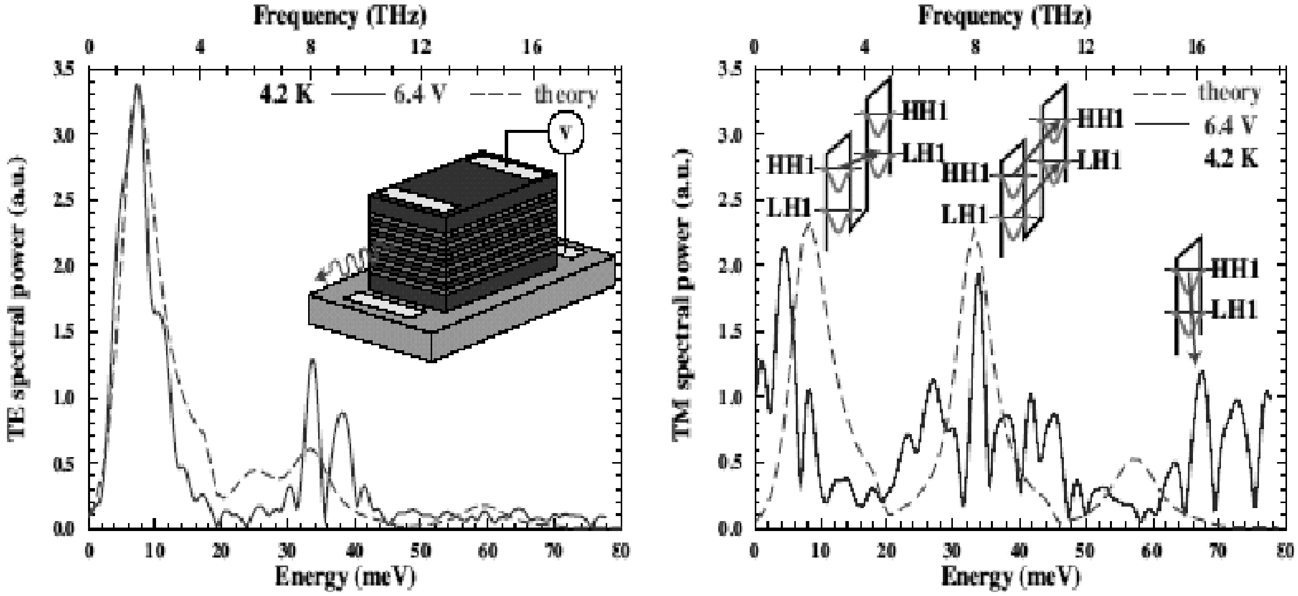

Fig. 12 TE and TM polarized emission from two kinds of quantum cascade devices [18].

will play the main role and therefore, intensive studies on SiGe heterostructures are largely required.

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