Preface

This volume contains papers presented at the EMRS Spring Meeting (Symposium B) held at Strasbourg (France) May 27–31, 1991.

This three-day Symposium, including the Plenary Session of all the EMRS meetings, was organized to promote scientific exchange in the field of new materials and modern sensors. Progress in material research, recent developments in growth techniques, as well as in processing technology and modelling, have a great impact on sensors.

The field of sensor research is interdisciplinary. This provides an opportunity for an intellectually stimulating meeting. All the papers published in this volume have been subjected to the refereeing procedures of the journal *Sensors and Actuators*. I thank the authors and the referees for their work in completing this volume.

I am grateful to all those who contributed to the success of the Symposium: the Committee members, the Session Chairmen, the speakers and the audience.

On behalf of all the participants, I thank the following sponsors for the financial support which made the Symposium possible:

- Centre National de la Recherche Scientifique
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Cet ouvrage rassemble les contributions présentées au Congrés EMRS (Symposium B) qui s'est tenu à Strasbourg (France) du 27 au 31 Mai 1991.

Cette réunion de trois jours, y compris la session pleinière commune aux divers Symposia EMRS, a été organisée de façon à promouvoir les échanges dans le domaine des nouveaux matériaux et des capteurs modernes.

Les progrés dans la recherche sur les matériaux, les développements récents des techniques de croissance, des technologies d'élaboration ainsi que de la modélisation ont un impact important sur l'évolution des capteurs. Le domaine de la recherche sur les capteurs est par nature interdisciplinaire. Il en résulte la possibilité d'échanges nombreux et stimulants.

Tous les articles publiés dans ce volume ont été soumis à des rapporteurs selon la procédure usuelle du journal *Sensors and Actuators*.

Je tiens à remercier les auteurs et les rapporteurs pour leur travail qui a permis la publication de cet ouvrage.

Je voudrais aussi remercier tous ceux qui ont contribué au bon déroulement de ce Symposium les membres du comité, les présidents de session, les orateurs, l'audience.

Au nom de tous les participants, je tiens à remercier ceux qui nous ont soutenus financièrement et ont aussi permis l'organisation de ce Symposium:

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High-lifetime strained $Si_{1-x}Ge_x$ films grown by rapid thermal chemical vapor deposition

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Abstract

The electrical and optical properties of strained epitaxial $Si_{1-x}Ge_x$ films on silicon have been examined to determine the potential application of the material for integrated infrared sensors on silicon substrates. The generation lifetime in films grown by rapid thermal chemical vapor deposition was found to be in excess of $1\ \mu s$, which is important for the fabrication of sensors with high shunt impedances. By comparison of the well-resolved photoluminescence of these films with absorption data, it is also concluded that the initial absorption mechanism in these alloys proceeds by a no-phonon process, despite the fact that the films have an indirect bandgap.

Introduction and growth reactor

It has been known for several years that alloys of silicon and germanium ($Si_{1-x}Ge_x$) can be grown commensurate on silicon substrates by growing strained layers [1, 2]. These commensurate strained layers are useful not only because of the absence of misfit dislocations which could adversely affect performance, but also because the strain splits the degeneracies otherwise present at the band edges to further lower the bandgap [3]. Because of this reduced bandgap, it has been proposed and demonstrated that these layers can be used as detectors in the near-infrared region ($1.3–1.5\ \mu m$) to integrate opto-electronic interconnect functions directly onto silicon VLSI circuits [4, 5]. This paper examines two fundamental properties of these films which are important for understanding their potential for this application. These properties are the lifetimes achievable and the fundamental optical absorption mechanisms.

Most $Si_{1-x}Ge_x$ strained-layer-growth work to date has been by molecular beam epitaxy (MBE) (as described in refs. 1 and 2) or by UHV Chemical Vapor Deposition (UHVCVD) [6]. These are both UHV techniques. The results described in this paper were measured in samples grown by Rapid Thermal Chemical Vapor Deposition (RTCVD), a non-UHVCVD technique that com-bines susceptorless lamp-heating and a transparent quartz tube as a reaction chamber with CVD technology (Fig. 1). The reactor configuration is similar to that of Limited Reaction Processing (LRP) [7], except that rapid gas switching, as opposed to rapid switching of the sample temperature, is used to switch the growth reaction on and off. The reactor is exhausted by a mechanical rotary vane pump. The growth is done at 6 Torr using dichlorosilane and germane in a hydrogen carrier. Silicon epitaxial layers are typically grown from 700 to 1000 °C, and $Si_{1-x}Ge_x$ layers from 600 to 625 °C. The wafer temperature during growth is controlled to within a few degrees centigrade during growth by *in situ* measurement of the infrared absorption in the silicon substrate [8]. Other growth details can be found in ref. 9.

Minority carrier properties

Given a semiconductor with a bandgap less than that of the photon energy to be detected, the most straightforward way to make a high performance detector is a p-i-n diode configuration. If $Si_{1-x}Ge_x$ is to be used, it may be desirable to incorporate the alloys in the i-region of the detector in a superlattice configuration [4, 5]. A primary motivation for integrating such a detector onto a silicon chip is
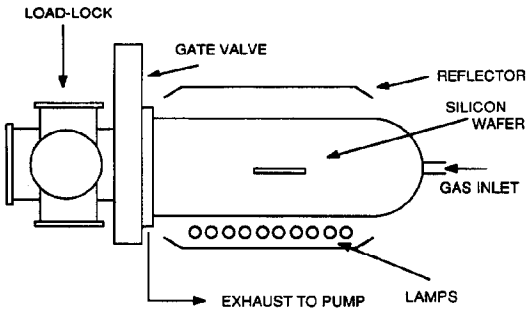
Fig. 1. Cross-section schematic of the RTCVD growth reactor. Not shown are the pumping apparatus, gas handling manifold, and the apparatus for the *in situ* measurement of the substrate infrared transmission for temperature measurement.
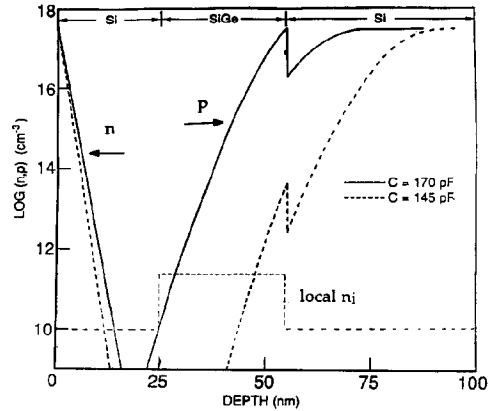

Fig. 2. Logarithm of carrier profiles as a function of depth for the buried $Si_{0.82}Ge_{0.18}$ at two points during its recovery from deep depletion. Also shown as a reference is the local n_i as a function of thickness.

hopefully to derive increased performance by having reduced electrical parasitics as compared with a hybrid-mounted approach. To achieve high performance from such p-i-n detectors, it is critical that their shunt resistance be as large as possible. A small shunt resistance will limit the maximum gain available from any transimpedance amplifier used in this application to convert the detected photocurrent signal to a voltage. A large shunt resistance will mean that a high generation lifetime is required of the detector material to decrease its leakage current.

The generation lifetime of the $Si_{1-x}Ge_x$ films may be probed through the use of the well-known technique of recovery of an MOS capacitor from deep depletion, since the recovery from deep depletion occurs through the generation of minority carriers. Special considerations must be taken when applying this technique to $Si_{1-x}Ge_x$ films, however. First, because of the generally poor electrical quality of the $SiO_2/Si_{1-x}Ge_x$ interface, it is necessary to place a thin Si cap layer on top of the alloy so that the oxide interface is with silicon [10]. Second, one must consider the basic nature of the generation process, described here by a simplified form of the SRH equation

$$G = n_i^2/\tau_0(n + p + 2n_i) \tag{1}$$

where $\tau_0 = (\sigma N_T v_{th})^{-1}$. G is the generation rate, n and p are electron and hole densities, respectively, n_i is the intrinsic carrier density, N_T is the trap density, σ the trap cross section, v_{th} is an average thermal velocity, and τ_0 is defined as the lifetime. In the case when both n and p are small compared with n_i, this expression reduces to

$$G = n_i/2\tau_0 \tag{2}$$

This last expression is the one which is commonly used to interpret any experiment where generation is taking place, including reverse biased p–n junctions. It is clear from these expressions that if the carrier concentrations n and p are greater than n_i, then the generation rate will be greatly suppressed compared with that predicted by eqn. (2). If eqn. (2) is then used in this case to extract a lifetime, a false high lifetime will be extracted. Therefore it is important to insure that both n and p are small compared with n_i in the region being probed for an accurate measurement of the generation lifetime, τ_0. We have performed numerical simulations of our capacitor test structures to examine the carrier densities in the $Si_{1-x}Ge_x$ regions under test during the capacitive transient (Fig. 2) [10]. As can be seen, during the times when the capacitance is between 145 and 170 pF, a substantial part of the $Si_{0.82}Ge_{0.18}$ region under investigation fulfills the above criteria, so that eqn. (2) is truly applicable to describe G. In this case, generation lifetimes of the order of 1 μs were found for the alloy films. This represents the highest lifetime yet reported for SiGe alloy films grown by any technique. It should be noted, however, that to achieve these results extreme care had to be taken to grow films with low oxygen concentrations (i.e., $\leqslant 10^{18}$ cm^{-3}). Although this required the use of a load-lock-transfer-assembly to load samples before growth without venting the growth chamber, UHV conditions were not at all required.

Fundamental absorption mechanisms

As demonstrated in refs. 4 and 5, $Si_{1-x}Ge_x$ can be used for optical detectors at 1.3 μm. In this section, the fundamental absorption process is investigated. Because of the high lifetime and atomic level uniformity in the films grown by RTCVD, these films have exhibited the first, well-resolved, band-edge photoluminescence (PL) of such strained films and quantum wells grown by any technique [11]. In a typical spectrum, shown in Fig. 3, one can readily identify the peaks by comparison with the results of the extensive work on relaxed bulk $Si_{1-x}Ge_x$ films of Weber and Alonso [12]. The large, high energy peak is a no-phonon (NP) peak resulting directly from re-combination of bound excitons. Phonon replicas corresponding to the TA and various local TO modes are also identifiable. Of great interest is the NP peak which persists to very high temperatures (over 200 K) even though the excitons are no longer localized. This NP recombination can still occur in the indirect material since it is a random alloy. The potential is no longer perfectly periodic, and Bloch wavefunctions are no longer exact eigenstates of the system. k, then, is no longer a good quantum number, and all states consist of many k-components mixed in by perturbation theory. This signal is of interest here since NP PL implies an NP optical absorption process as well.

Figure 4 compares bandgaps extracted from the NP PL signal versus composition, and the absorption edges extracted from photocurrent measurements in p-i-n diodes [13]. If a phonon were required for the absorption process, one would expect the absorption edge to be above the PL
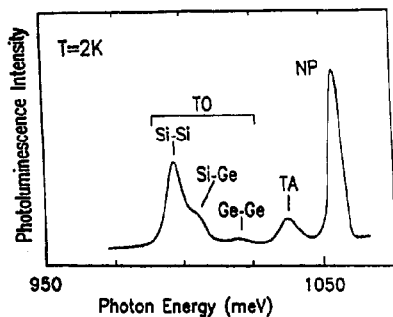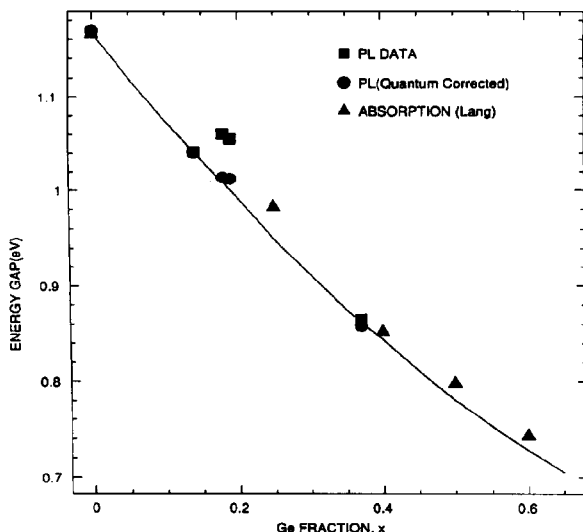

Fig. 4. Bandgaps of strained $Si_{1-x}Ge_x$ layers vs. composition. Bandgaps were determined by the NP PL line and corrected for quantum confinement effects (indicated) and excitonic binding energies and corrected to 0 K. For comparison the bandgap by absorption spectroscopy is also shown [13].

bandgap by a phonon energy (i.e., 30–60 mV). That this is not observed implies that the initial absorption mode is indeed a no-phonon process, consistent with the strong NP emission process. This conclusion contradicts the interpretation of Braunstein et al. [14] of absorption measurements on relaxed alloy films. That work concluded that the dominant absorption process was phonon-assisted, and subtracted a phonon energy from the absorption edge to find a bandgap. Their bandgaps of relaxed films are consistently lower than those found by PL [12] by approximately a phonon energy, suggesting that indeed a no-phonon absorption process is also occurring in relaxed alloys.

Fig. 3. Typical photoluminescence spectrum of a $Si/Si_{0.82}Ge_{0.18}/Si$ multi-quantum well structure at 2 K.

Conclusions

Fundamental properties of $Si_{1-x}Ge_x$ films for infrared detectors on silicon substrates have been investigated. Generation lifetimes in the range of 1 μs have been observed in layers grown by RTCVD. From a comparison of well-resolved PL spectra and absorption measurements, it is concluded that the initial absorption process does not involve a phonon.

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