Increase Responsivity in $Ge_{1-x}Sn_x$ QWs photodetectors

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In recent years, Ge has been considered as a suitable material for lasers and photodetectors (PD) because its electronic band gap is compatible with optical fiber and waveguide applications [1]. Besides, Ge can be grown onto Si, which enables integration next to CMOS on a Si platform. The use of Ge in PD requires a thick active Ge layer without dislocations, which would act as unwanted optical absorption centers.

For optical interconnects, the introduction of Sn into Ge has been considered as it offers an increase in the responsivity in PDs [2]. It has been reported that $Ge_{1-x}Sn_x$ has a higher absorption coefficient than Ge [3]. Only 0.25% substitutional Sn in Ge already results in an increase of the responsivity of PIN PD to longer wavelengths (above 1600 nm) [2]. Therefore, a higher responsivity is expected if we can synthesize sufficiently thick $Ge_{1-x}Sn_x$ while preventing the introduction of dislocations in the layer. In addition, significantly higher substitutional Sn concentrations are needed to obtain higher responsivities in the entire wavelength range of the device (750 – 2400nm), as demonstrated in this work. Despite the low Sn solubility in the Ge lattice of <1%, we could recently demonstrate the epitaxial growth of strained and relaxed $Ge_{1-x}Sn_x$ layers with Sn concentrations above 11%, which are fully substitutional as long as layer relaxation is prevented (Fig. 1) [4]. However, above a composition dependent critical thickness, $Ge_{1-x}Sn_x$ relaxes by the formation of dislocations and Sn precipitation.

The use of a thick strain relaxed Ge layer as a buffer is a well known technique to overcome the large lattice mismatch between $Ge_{1-x}Sn_x$ and Si. However, even if the $Ge_{1-x}Sn_x$ layer is grown on a relaxed Ge buffer layer, strain relaxation is expected above a Sn dependent critical layer thickness [4]. Therefore, we suggest to use strained $Ge_{1-x}Sn_x$ quantum wells (QWs) on a Ge buffer layer. This allows an increase of the total $Ge_{1-x}Sn_x$ thickness without introducing strain relaxation by the formation of dislocations. Besides, using a QW structure results in an increase of the density of states due to quantum effects. This also contributes to a higher responsivity of PDs, in addition to the increase related with the higher absorption coefficient by adding Sn. In this work, we demonstrate the fabrication of Ge/$Ge_{1-x}Sn_x$ layer stacks enabling an increase responsivity of PDs and we will discuss the dependence of the $Ge_{1-x}Sn_x$ QW responsivity on the Sn content in the $Ge_{1-x}Sn_x$ QW and on the number of QWs.

The $Ge_{1-x}Sn_x$/Ge heterostructures are grown by atmospheric chemical vapor deposition in an Epsilon like equipment from ASM. The $Ge_{1-x}Sn_x$/Ge are grown on 200 mm Si substrates which contain 500 nm-thick relaxed Ge buffer layers on top of it. 20 or 40 nm-thick compressively strained $Ge_{1-x}Sn_x$ (st-GeSn) QWs with Sn content ranging from 0 to 10% were grown separated by Ge barrier layers. Ge_2H_6 and $SnCl_4$ were used as precursors. Fig. 2 shows X-ray diffraction (XRD) measurement together with the modeling for a 25 nm-thick $Ge_{1-x}Sn_x$ layer with Sn content of 7% on Ge/Si. The XRD measurements reveal a pseudomorphic growth of the $Ge_{1-x}Sn_x$ layer on Ge buffer layer. Comparing with the modeling of the layers on a Ge substrate, we obtain a good correlation, showing a high crystallographic quality of the $Ge_{1-x}Sn_x$/Ge heterostructure. Bright photo luminescence (PL) also confirms good material quality in terms of low defectivity for our $Ge_{1-x}Sn_x$ layer with a Sn content of 6.0% and 8.5% [5].

Figure 3 shows the responsivity measured by Fourier Transform Infrared spectroscopy (FTIR) for fully strained $Ge_{1-x}Sn_x$ with various Sn contents (Ge cap = 50 nm, $Ge_{1-x}Sn_x$ QW = 40 nm). Sn introduction clearly increases the responsivity, as expected [6]. Additionally, the detectable range is expanded due to shrinkage of the bandgap energy. From this result, we estimated a bandgap of 0.63eV and 0.57eV for a Sn content of 5% and 9%, respectively. On the other hand, Figure 4 shows the dependence of the responsivity on the number of $Ge_{1-x}Sn_x$ QWs (Sn content=10%, Ge cap = 100 nm, $Ge_{1-x}Sn_x$ QW =

20 nm, number of QWs = 1, 2 and 3). As expected, a higher responsivity can be achieved when the number of $Ge_{1-x}Sn_x$ QWs is increased. We calibrated the responsivity for $Ge_{1-x}Sn_x$ QWs by using surface illumination. As a result, the $Ge_{1-x}Sn_x$ PD has higher responsivity over the whole wavelength range compared to a Ge PD. In summary, we were able to demonstrate that the introduction of Sn and an increase of the number of $Ge_{1-x}Sn_x$ QWs results in an effective increase of the photoconductor responsivity.

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References

1. J. Liu, *et al.*, Opt. Exp. **15**, 11272 (2007).
2. R. Roucka, *et al.*, Appl. Phys. Lett. **109**, 103115 (2011).
3. V. R. D'Costa, *et al.*, Semicond. Sci. Technol. **24**, 115006 (2009).
4. F. Gencarelli, *et al.*, ECS Trans. **50** (9), 875 (2012).
5. S. Gupta, *et al.*, IEDM Tech. Dig. (2012) *To be published.*
6. A. Gassenq, *et al.*, Opt. Exp. **20**, 27288 (2012).

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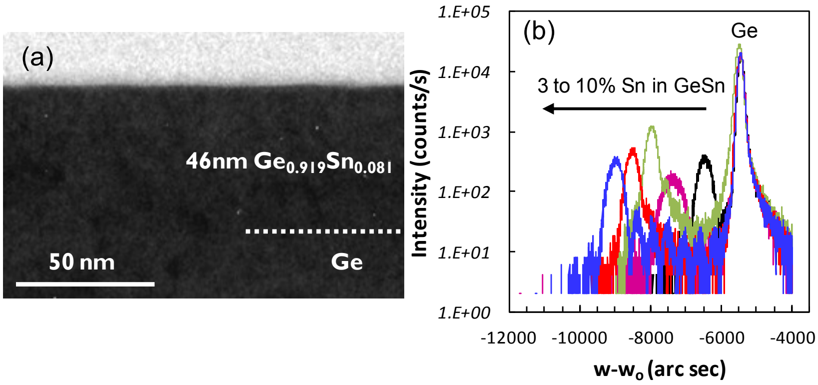

Fig. 1 (a) Cross-sectional TEM image for fully strained $Ge_{1-x}Sn_x$ on Ge/Si. (b) XRD (004) 2θ-ω scan for fully strained $Ge_{1-x}Sn_x$ layers with Sn content from 3 to 10%.

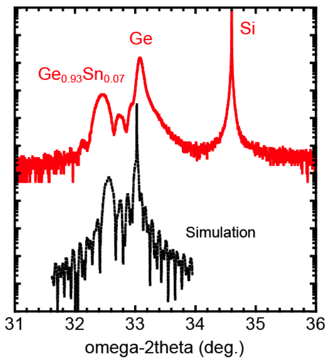

Fig. 2 Measured (solid line) and simulated (dashed line) XRD (004) 2θ-ω scan of the 25 nm $Ge_{1-x}Sn_x$ with Sn content of 7% strained QW on Ge with a 100 nm Ge cap layer.

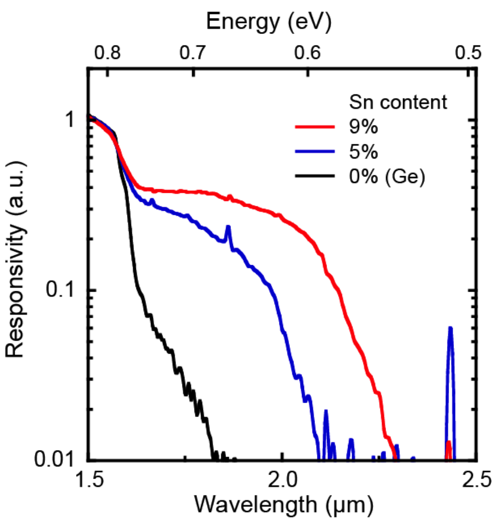

Fig. 3 Responsivity for Ge(Sn) QW with various Sn content measured by FTIR (Ge cap = 50 nm, $Ge_{1-x}Sn_x$ QW = 40 nm).

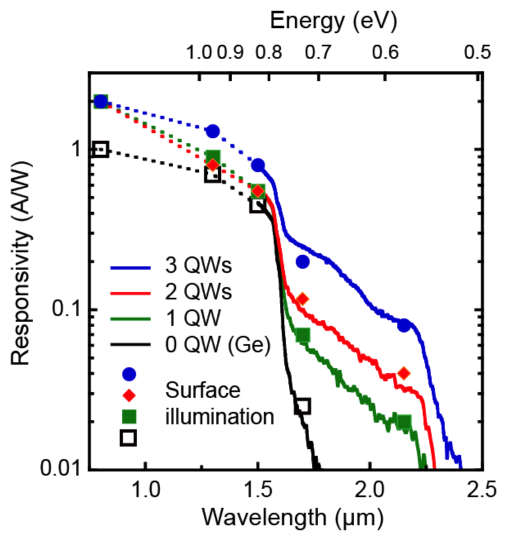

Fig. 4 Responsivity for $Ge_{1-x}Sn_x$ QWs with various a number of QWs measured by FTIR and calibrated by using laser-based surface illumination (Sn content = 10%, Ge cap = 100 nm, $Ge_{1-x}Sn_x$ QW = 20 nm, a number of QWs = 1, 2 and 3).