SiGe quantum wells for uncooled long wavelength infra-red radiation (LWIR) sensors

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Abstract
We demonstrate a novel single-crystalline high-performance thermistor material based on SiGe quantum well heterostructures. The SiGe/Si quantum wells are grown epitaxially on standard Si [001] substrates. Holes are used as charge carriers utilizing the discontinuities in the valence band structure. By optimizing design parameters such as the barrier height (by variation of the germanium content) and the fermi level Ef (by variation of the quantum well width and doping level) of the material, the layer structure can be tailored. Then a very high temperature coefficient of resistivity (TCR) can be obtained which is superior to the previous reported conventional thin film materials such as vanadium oxide and amorphous silicon. In addition, the high quality crystalline material promises very low 1/f-noise characteristics promoting an outstanding signal to noise ratio as well as well defined and uniform material properties.

High-resolution X-ray diffraction was applied to characterize the thickness and Ge content of QWs. The results show sharp oscillations indicating an almost ideal super lattice with negligible relaxation and low defect density.

The impact of growth temperature on the thermistor material properties was characterized by analyzing how the resulting strain primarily affects the performance of the TCR and 1/f noise. Results illustrate a value of 3.3 %/K for TCR with a low 1/f noise.
1. Introduction

Infrared sensors are classified by their detection standard into photon- [1, 2] and thermal-based principles [3, 4]. The first type is based on the creation of electrons or holes in a semiconductor material, followed by subsequent collection and amplification of the signal. The thermal-based devices operate on the thermoresistance properties of a material. In this case, the suitable materials should have a large temperature coefficient of resistance (TCR), low values of noise and thermal conductivity, and ability of integration into standard technological processes.

Different reports have proposed Vanadium oxide (VOx) [5], amorphous semiconductors [6, 7] and poly SiGe [8, 9] as thermistor material. Meanwhile, implementing of single-crystalline SiGe layers has not been investigated in detail. This paper presents single-crystalline SiGe grown by CVD as a high-performance thermistor material.

2. Experimental details

SiGe/Si stack (with the well and barrier widths were 50 and 350 Å thick, respectively) was grown on 100 mm Si wafers in an RPCVD reactor at 650-700 °C with total pressure 20 torr. The samples were cleaned using an ex-situ cleaning procedure and immediately loaded to the N₂-purged load-lock. Dichlorosilane (SiCl₂H₂) and 10% germane (GeH₄) in H₂ were used as Si and Ge precursors, respectively. The Ge amount and layer thickness were measured directly by high resolution x-ray diffraction (HRXRD). The noise measurements were performed by using a set-up which consists of a battery powered bias network, an EG&G 5113 low-noise preamplifier and an HP89410A vector signal analyzer.

3. Results & Discussions

The XRD measurements (figure 1) showed crystalline properties with a 35% germanium content. No relaxation was observed.

In general, coefficient of resistivity, TCR, is defined as:

\[ \beta = \frac{1}{R} \frac{\partial R}{\partial T} \]  

(1)

Figure 1. XRD rocking curve of the investigated quantum well structures. No relaxation was observed.
where $R$ is the resistance of the material and $T$ is the applied temperature. For a semiconducting material, $1/R$ is proportional to the amount of free carriers, $p_{exc}$ (as in this case of p-doping) [10], hence the temperature coefficient can be calculated and derived to the quantum well’s barrier- and fermi energy level by:

$$\beta = -\frac{1}{k_BT^2} \left( \frac{3}{2} k_B T + E_f - V \right)$$  \hspace{1cm} (2)$$

where $k_B$, $V$, and $E_f$ are Boltzmann’s constant, barrier energy and Fermi level, respectively. Figure 2 shows a schematic diagram of the valence band (p-type) structure of a single quantum well.

By varying the germanium content the barrier height can be changed. The Fermi level can be controlled by the width and doping level of the quantum well. In this way the structures can be tailored to maximize the needed TCR characteristics.

Theoretical TCR values have been simulated using a model including strain, and varying the germanium content, doping levels and quantum well widths (figure 3). The main limitation in designing the quantum well is the lattice miss-match between crystalline silicon and germanium. For maximum feasible germanium content of about 40% a TCR value of 3.5 %/K can thus be achieved.

![Fig. 2. Valence band structure of SiGe/Si quantum wells.](image)

![Fig. 3. TCR of Si/SiGe multi-layer structures with different Ge content. The dashed line shows simulated values using a strained model with background doping of 2 $10^{-16}$. The points are measured values from epitaxially grown multi-well structures after metal contact anneal.](image)

The thermistor structure has a vertical functionality and the current is thus transported from the top to the bottom contact. The TCR was measured to be 3.3 %/K with a high uniformity (< ± 2%, figure 4).
Fig. 4. TCR uniformity over 100 mm wafer of epitaxially grown Si/SiGe multi-layer structure with 35% Ge content. The material is deposited on a 200 mm wafer, and cut into two 100 mm wafers for further processing. Trench etching and metallization followed by 350 °C anneal.

For germanium levels below 30% (figure 3) the measured values are far below the theoretical values. The discrepancy is still to be investigated.

Figure 5 shows noise measurements performed on the thermistor structure. We have obtained promising results which however show higher values than an ideal reference resistor.

Fig. 5. Noise measurement of Si/SiGe multilayer thermistor structure. 600 Ohm structure. The K value calculated from 1 Hz to 1 KHz is below $10^{-27} \text{m}^3$, compared to $10^{-28} \text{m}^3$ for the reference resistor.

The inherent NETD (noise equivalent temperature difference), an important performance parameter in infrared imaging, is proportional to TCR an inversely proportional to noise. Combined with low cost
MEMS and CMOS compatible manufacturing techniques [11], these material parameters will result in a very competitive NETD in regards to VOx and amorphous silicon bolometers.

4. Conclusions
SiGe based quantum well structures with a high germanium content results in a high temperature coefficient of resistivity. As high as 3.3 %/K has been obtained. Using a high temperature DCS based growth process results in obtaining a high TCR as well as high resistivity. Some evidence show however that this may also lead to a higher g-r noise. This is primarily caused by strain. Limited improvements can be made using high quality substrates, pre-processing cleaning procedures and optimized epitaxial processes (i.e. carbon doped) minimizing defects in the interfaces of the heterostructure. Having another type of structure (quantum wire or quantum dot) where the accumulated strain is significantly lower will most probably reduce the overall noise contribution.

5. References
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