Fast time response from Si–SiGe undulating layer superlattices

D. Buca, S. Winnerl, S. Lenk, and Ch. Buchal[a)]
Institut für Schichten und Grenzflächen, ISG–IT, Forschungszentrum Jülich, D-52425 Jülich, Germany

D.-X. Xu
National Research Council, Ottawa, Ontario KIA OR6, Canada

(Received 28 January 2002; accepted for publication 15 April 2002)

We have grown Si–$Si_{1-x}Ge_x$ undulating layer superlattices with $x=0.39$ and 0.45 by molecular-beam epitaxy on top of epitaxial implanted $CoSi_2$ layers and fabricated vertical metal–semiconductor–metal detectors. The detectors show a quantum efficiency of 5% for the wavelength of 1320 nm and 0.9% for 1550 nm. We performed temporal response measurements, using a Ti:sapphire laser and an optical parametric oscillator which generates ultrafast pulses at infrared wavelengths. An electrical response time of 16 ps full width at half maximum was obtained at a wavelength of 1300 nm. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1483121]

The expansion of optical fiber communication networks stimulates research for infrared detectors at $\lambda=1300$ and 1550 nm, which are compatible with silicon technology.[1] Ge or SiGe alloys with high-Ge content are attractive candidates for detector materials. However, due to the large lattice mismatch of 4.2% between Ge and Si, thick graded buffer layers of 1 μm buffer layer thickness for every 10% Ge content are required for epitaxy.[2,3] Due to the buffer thickness such structures are not attractive. An alternative concept is the growth of Si–SiGe superlattices with strained layers. Strain induces a lowering of the energy gap. For $\lambda=1300$ nm, Si–$Si_{0.5}Ge_{0.5}$ superlattice *pin* diodes have been demonstrated in waveguide geometry[4] and for free-beam incidence.[5] It has been shown that metastable Si–$Si_{0.5}Ge_{0.5}$ strained undulating superlattices with a transition energy of 0.8 eV, corresponding to a wavelength of 1550 nm, can be grown with a low defect density.[6,7] Recently, Si–$Si_{0.5}Ge_{0.5}$ undulating layer superlattices have been grown by ultra-high-vacuum chemical-vapor deposition.[8] Photoluminescence at 1550 nm has been reported for this material.[9]

We have extended the use of undulating layer superlattices to ultrafast metal–semiconductor–metal (MSM) detectors, using a buried layer of epitaxial $CoSi_2$ as a bottom electrode. The results are compared to MSM detectors of similar geometry, made from silicon only.[10]

We started with Si(100) float-zone phosphorus-doped wafers of 100 mm diam as substrates ($\rho>1$ kΩ cm). To provide a buried metallic contact, 90-nm-thick epitaxial $CoSi_2$ layers were formed by ion implantation and subsequent rapid thermal annealing.[11] After an RCA cleaning procedure the implanted wafers were shipped to the National Research Council, Ottawa and processed in a molecular-beam-epitaxy (MBE) system to form the undulating superlattices. They consist of ten periods with nominal thickness of 12 nm Si and 5 nm SiGe, which are sandwiched between a 120-nm-thick Si buffer layer and a 90-nm-thick cap layer. The growth temperature was 600 °C. The Si layers were grown at a rate of 0.15 nm/s, while for the SiGe layers a rate of 0.03 nm/s was used for both Si and Ge.

In Fig. 1 we show a cross-sectional transmission electron micrograph (TEM) of the superlattices. The vertical ordering of the Ge-rich crests is due to local stress developing during the Stransky–Krastanov growth.[9,12] Threading dislocations extending from the $CoSi_2$ layer to the surface are visible. Rutherford backscattering spectrometry (RBS) was used to measure the total thickness of the superlattice and the average composition, as well as the thickness of the Si cap layer. Wafers with average Ge contents of 39 and 45 at. % were used to fabricate the MSM detectors. Mesa structures with diameters from 30 to 100 μm were formed by standard lithography and reactive ion etching. A transparent Cr contact (8 nm thick) served as the top electrode. This results in a plate capacitor structure with 400 nm Si–SiGe–Si between the electrodes and a total capacitance of approximately $C_{\mathrm{det}}=200$ fF, see Fig. 2(a). The detector is connected to a microstrip line with a calculated impendance of $R=12\ \Omega$. This leads to a calculated RC_{det} time constant of $\tau=2.4$ ps.

Both electrodes form Schottky contacts, and since for both contacts the Schottky barriers for holes are lower than for electrons, the hole current dominates the dark current. From the current–voltage characteristics Schottky barrier heights of $\Phi_{h\mathrm{CoSi}_2}=0.31$ eV for holes at the $CoSi_2$–Si interface and $\Phi_{h\mathrm{Cr}}=0.48$ eV for the Cr–Si interface were extracted. At room temperature, the dark current density is 15

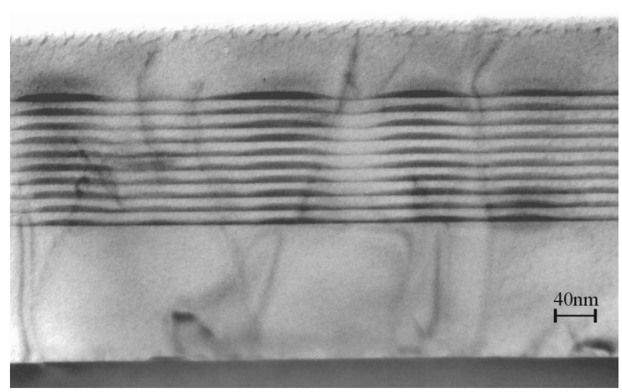

FIG. 1. Transmission electron microscopy image of a MBE-grown Si–SiGe superlattice. Ge content is 39 at. %.

[a)]Electronic mail: c.buchal@fz-juelich.de

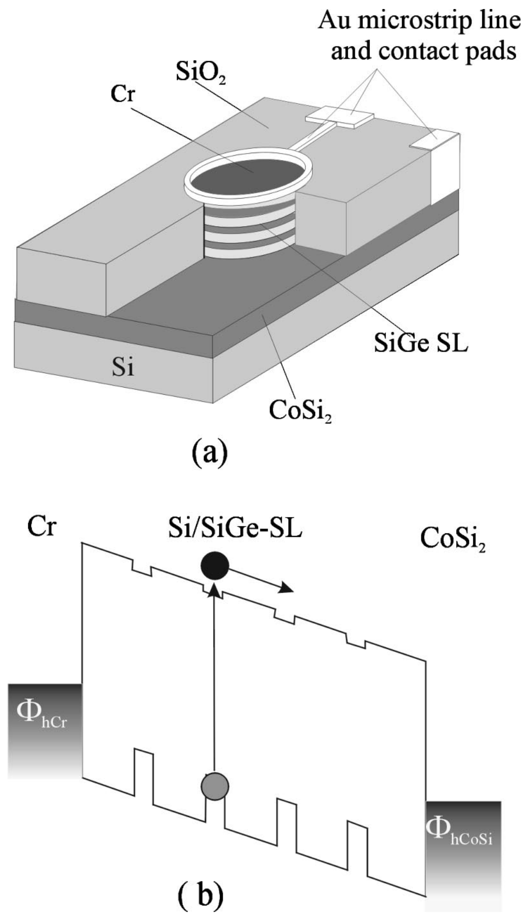

FIG. 2. Detector design (a) and band diagram (b) for a SiGe SL detector.

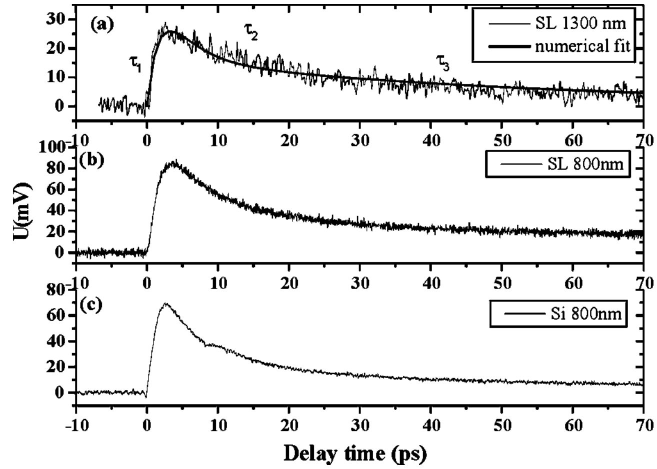

FIG. 3. Electrical response from a 39 at. % SiGe SL detector at $\lambda = 1300$ (a); $\lambda = 800$ nm (b) and a pure Si MSM detector at $\lambda = 800$ nm (c).

mA/cm^2, if a voltage of +1 V is applied to the Cr electrode. The Schottky barrier between $CoSi_2$ and Si is somewhat lower than the expected theoretical value of 0.4 eV, which hints to some imperfections at the interface. The dc photocurrent is the difference between the current under illumination and the dark current. It is used to calculate the responsivity and the overall quantum efficiency of the detectors. For a sample of 45 at. % Ge, we found values for the quantum efficiency of 5.2% for $\lambda = 1320$ nm and 0.9% for $\lambda = 1550$ nm. For 39 at. % Ge we found 1.6% and 0.03%, respectively. The detectors with 45% Ge have a 100 times higher quantum efficiency than a similar Si–$CoSi_2$ Schottky barrier detector.[1] Obviously, in the SiGe superlattice detector, electron–hole pairs are created in the Ge-rich regions. Our data indicate that the absorption coefficient at the wavelength of 1300 nm in the Ge-rich regions may approach the absorption coefficient of pure Ge. Furthermore, the absorption efficiency of the device is enhanced by multiple reflexions, because the semiconductor and the electrodes form an optical cavity [Fig. 2(a)].

Energy-band alignment studies of the SiGe–Si heterostructure have shown that the change Δ of the band gap E_g leads to a small offset in the conduction band ($10\% \times \Delta$) as compared to the offset in the valence band ($90\% \times \Delta$).[13] Therefore, electrons move freely across the SiGe–Si interfaces at room temperature ($E_{C,\mathrm{Si}} - E_{C,\mathrm{SiGe}} \sim 25$ meV), but the holes are mostly trapped in the quantum wells ($E_{V,\mathrm{Si}} - E_{V,\mathrm{SiGe}} \sim 250$ meV), see Fig. 2(b). The density of the photogenerated carriers in the wells remains larger than in the Si regions and recombination takes place in the quantum wells. Although in Si and Ge a direct radiative recombination is prohibited, in the undulating SiGe structure with Ge-rich regions significant photoluminescence at 1550 nm was measured.[14] Probably, the recombination rate in the quantum wells is strongly enhanced if compared to uniform material. This shortens the electrical response time of the detectors.

The temporal response of the photodiodes is measured by an optical pump–probe technique.[10] For 700–900 nm, a Ti:sapphire laser provides pump and probe pulses of 150 fs full width at half maximum (FWHM). An additional optical parametric oscillator is used for generating infrared optical pulses. The photoexcited carriers in the detector under investigation give rise to an electrical pulse traveling along the microstrip transmission line. An optical probe pulse samples the electrical pulse with the help of an electro-optical crystal. Figure 3(a) shows the fast response of a detector with 39 at. % Ge and a sensitive area of 900 μm^2, measured at a pump wavelength of 1300 nm. The observed result of 16 ps FWHM represents a fastest response to infrared radiation obtained from a SiGe detector. It was measured at 300 K.

For comparison, we have studied a series of different MSM detectors of different sizes, made from pure Si. This allows us to separate the contribution of carrier drift and *RC* time constants to the observed device response speed. The smallest device (80 μm^2) is the fastest with a total response time of 3.2 ps FWHM. This response is determined by the drift time of the photogenerated carriers, which are accelerated to saturation drift velocity ($\sim 10^7$ cm/s).[10] The larger devices with areas up to 4000 μm^2 show increasing contributions from the electrical *RC* time constants, which increase the total response time.

As shown in Figs. 3(a)–3(c), we compare the response of a SiGe superlattice (SL) detector to the response of a pure Si MSM detector, which has the same area and thickness. The observed electrical signal $f(t)$ can be described by three exponential functions:

$$f(t) = a[1 - e^{(-t/\tau_1)}][e^{(-t/\tau_2)} + b e^{(-t/\tau_3)}].$$

The first factor represents the rising part of the signal, characterized by a time constant τ_1. The decay of the signal is composed by the sum of two exponential functions with time constants τ_2 and τ_3. The analysis yields values of $\tau_1 = 3$ ps, $\tau_2 = 3.8$ ps, and $\tau_3 = 70$ ps, for the SiGe SL detector with 39 at. % Ge. This may be compared to the response of a pure Si detector ($\tau_1 = 2.9$ ps, $\tau_2 = 3$ ps). The total current of the detectors is given by the contribution of the electrons and holes, which are accelerated by the homogeneous applied field. The duration of the internal current is equal to the electron or hole transit time to the electrodes.

In an ideal circuit, the rise time of the signal (τ_1) is extremely fast. In the experiment it is given by the RC_{ext} time constant of the external circuit, but not influenced by the detector capacity C_{det}. Therefore, the parameter τ_1 gives no information about the carrier dynamics. Due to the higher drift velocity of the electrons than of the holes, the total response is characterized by a fast component τ_2, reflecting the rapid sweep out of the electrons and a slower component τ_3, which is due to the holes. Comparing τ_2 in Si (3 ps) and the SiGe SL (3.8 ps), we conclude a 30% lower speed of the electrons in SiGe. This is due to a reduced mean-free path between the SiGe quantum wells. Another contribution to the long signal decay is carrier trapping and detrapping at defects. This is observed especially in devices of lower material quality.[4]

In conclusion, we have fabricated vertical Si–SiGe–Si/$CoSi_2$ MSM detectors on Si(100). Quantum efficiencies of 5% and 0.9% for $\lambda = 1320$ and 1550 nm, respectively, were obtained. Our detector showed a time response of 16 ps at a wavelength of $\lambda = 1300$ nm, which represents a fastest response to IR radiation obtained from a SiGe detector.

The authors gratefully acknowledge the earlier cooperation with M. Löken and support from the EU–LTR Project No. 31838 (SCOOP).

[1] H. Zimmermann, *Integrated Silicon Optoelectronics* (Springer, Berlin, 2000).
[2] K. L. Wang, S. Thomas, and M. O. Tanner, J. Mater. Sci. **6**, 311 (1995).
[3] G. L. Zhou and H. Morcoc, Thin Solid Films **231**, 125 (1993).
[4] A. Splett, T. Zinke, K. Petermann, E. Kasper, H. Kibbe, H.-J. Herzog, and H. Presting, IEEE Photonics Technol. Lett. **6**, 59 (1994).
[5] F. Y. Huang, X. Zhu, M. O. Tanner, and K. L. Wang, Appl. Phys. Lett. **67**, 566 (1995).
[6] D. C. Houghton, D. D. Perovic, J.-M. Baribeau, and G. C. Weatherly, J. Appl. Phys. **67**, 1850 (1990).
[7] D. D. Perovic, B. Bahierathan, H. Lafontaine, D. C. Houghton, and D. W. McComb, Physica A **239**, 11 (1997).
[8] H. Lafontaine, N. L. Rowell, S. Janz, and D.-X. Xu, J. Appl. Phys. **86**, 1287 (1999).
[9] H. Lafontaine, N. L. Rowell, and S. Janz, Appl. Phys. Lett. **72**, 2430 (1998).
[10] Ch. Buchal, M. Löken, Th. Lipinsky, L. Kappius, and S. Mantl, J. Vac. Sci. Technol. A **18**, 630 (2000).
[11] S. Mantl, Mater. Sci. Rep. **8**, 1 (1992).
[12] J.-M. Baribeau, J. Cryst. Growth **157**, 52 (1995).
[13] R. People, J. C. Bean, D. V. Lang, A. M. Sergent, H. L. Stormer, K. W. Wecht, R. T. Lynch, and K. Baldwin, Appl. Phys. Lett. **45**, 1231 (1984).
[14] D.-X. Xu, S. Janz, H. Lafontaine, and M. R. T. Pearson, Proc. SPIE **3630**, 50 (1999).