Ge on Si by Novel Heteroepitaxy for High Efficiency Near Infrared Photodetection

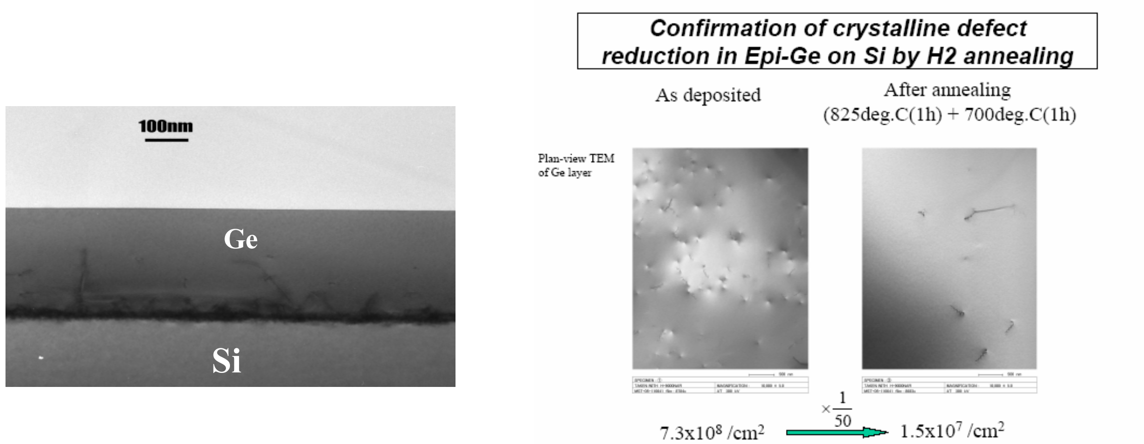
Ali K. Okyay, Ammar M. Nayfeh and Krishna C. Saraswat
Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
(email: aokyay@stanford.edu)
Ann Marshall, Paul C. McIntyre
Department of Materials Science and Engineering, Stanford University, Stanford, CA 94305
Takao Yonehara
Leading-Edge Technology Development Headquarters, Canon Inc., 5-1, Morinosato-Wakamiya, Atsugi, Kanagawa 243-0193, Japan

Abstract: We report germanium-on-silicon MSM photodetectors with responsivities as high as 0.85A/W at 1.55 m and 2V reverse bias, and exhibit reverse dark currents of $100mA/cm^2$ and external quantum efficiency up to 68%.

OCIS codes: (040.3060) Infrared; (040.5160) Photodetectors

Germanium has been emerging as a viable candidate for integration with Si for low-cost transceivers to overcome the spectral limit of Si photodetectors (PDs). Moreover, the interest is strengthened by its compatibility with Si CMOS technology, prompting researchers to focus on developing procedures for integration of SiGe and Ge PDs on Si [1-3]. Ge growth on Si is hampered by the large lattice mismatch (4.2%) resulting in growth that is dominated by islanding and misfit dislocations terminating at the film surface as threading dislocations, thus degrading device performance. We report high quality Ge based metal-semiconductor-metal (MSM-PDs) employing a recently developed procedure, *Multiple Hydrogen Annealing for Heteroepitaxy* (MHAH) [4], for growing high quality thick heteroepitaxial Ge layers on silicon.

Fig. 1(a) presents a cross sectional TEM image of a two step *MHAH* growth that yielded a ~ 400nm Ge layer. The image shows that near the surface the dislocation density is reduced while near the Si/Ge interface the dislocation density is very large. While Fig. 1(b) presents plan-view TEM images showing a 50× reduction in dislocation density, from 7.3 cm^{-2} to 1.5 cm^{-2}, comparing the as-grown case to a 1.5 m MHAH-Ge layer. 1 $1\mu m^2$ and 10 $10\mu m^2$ atomic force microscopy scans of the surface yielded a final surface roughness of 0.218nm and 2.9nm. Ge layers as thick as 4.5µm were grown using the MHAH method with reduced dislocation density.

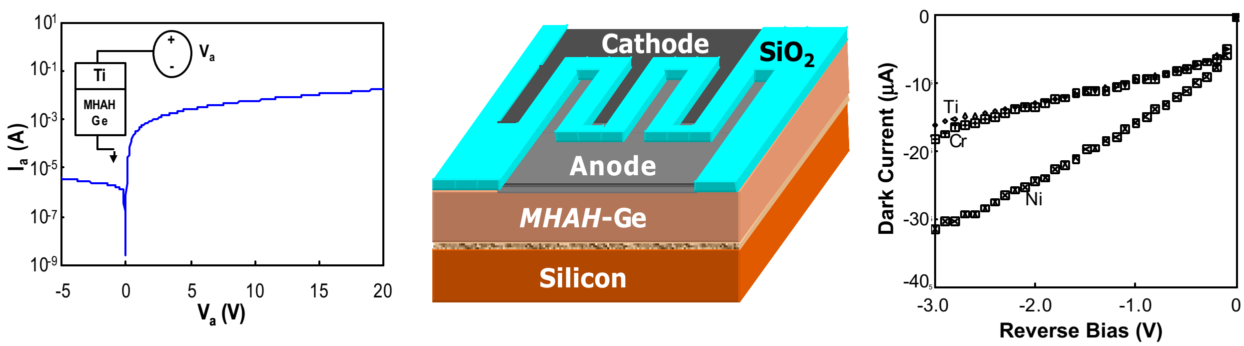


(a) (b)

Fig. 1. (a) Cross-sectional TEM image of ~400nm heteroepitaxial-Ge layer on Si grown by the *MHAH* method. (b) Plan-view TEM images showing 50x reduction of dislocation density using MHAH method to grow a 1.5µm Ge layer

Schottky diode behavior was verified on metal-semiconductor by current-voltage (*I-V*) characteristics as shown by Fig. 2(a), confirming the low defect density of the MHAH-Ge substrates. Fig. 2(b) shows the schematic of interdigitated MSM-PDs fabricated on 4.5 m high quality intrinsic *MHAH*-Ge layer on Si. Dark current versus the reverse bias voltage from symmetric MSM-PDs are plotted in Fig. 2(c) which show back-to-back Schottky diode.

Fig. 3(a) plots responsivity ( ) vs. reverse bias for Ti-Ge-Ti photodetectors operated at 1.55 m. We observe responsivities of 0.76A/W under 1V reverse bias, corresponding to 61% external quantum efficiency (η). The highest of 0.85A/W, corresponding to η ~ 68% was observed from a detector with 5 m electrode width and spacing. Under similar conditions, the theoretical maximum collection efficiency, for a film of 4.5 m thick, is 88% without accounting for reflections from the surface.



(a) **(b)** **(c)**

Fig. 2. (a) Current vs voltage characteristics of MS (Ti-Ge) Schottky diode on MHAH-Ge (b) Cross-section of MSM photodetector fabricated on MHAH-Ge layer grown on Si starting substrate. (c)Measured I_{dark} for symmetric metal-Ge-metal photodiodes with 5 m electrode width and spacing. Ti, Ni and Cr were used as electrode metals.

The measured I_{photo} versus E is found, for weak fields, to exhibit a linear relation as described by the Hect formula [5] but saturates for large values of E as shown in Fig. 3(b). Moreover, the photocurrent remains linear for over an order of magnitude in light intensity for various applied voltages showing the high optoelectronic quality of the Ge film.

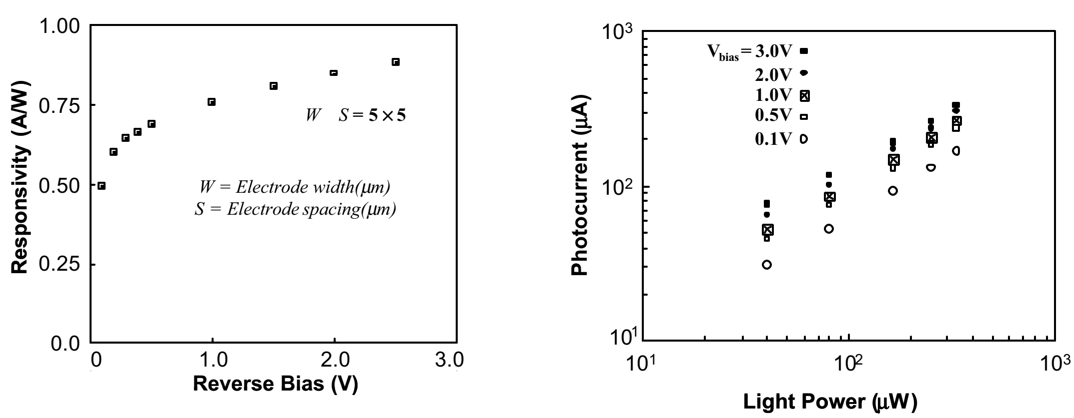


Fig. 3. (a) Photodetector responsivity at =1.55 m versus reverse bias for Ti-Ge-Ti MSM-PDs with 5 m finger width and spacing and 10^4 m^2 active area. (b) Photocurrent of the MSM device versus light power at m and different applied biases.

In summary, we present η ~ 68% MSM-PDs with 0.85A/W at 1.55 m in Ge integrated directly on Si using a novel technique that allows growth of high quality heteroepitaxial-Ge layers on Si.

References

[1] S. Luryi, A. Kastalsky, and J. C. Bean, "New infrared detector on a silicon chip," *IEEE Trans. Electron Devices,* vol. ED-31, pp. 1135-1139, Sept 1984.

[2] S. Fama, L. Colace, G. Masini, G. Assanto, H. C. Luan, "High performance germanium-on-silicon detectors for optical communications," *App. Phys. Lett.,* vol. 81, no. 4, pp. 586-588, 2002.

[3] L. Colace, G. Masini, G. Assanto, H. C. Luan, K. Wada, L. C. Kimerling, "Efficient high-speed near-infrared Ge photodetectors integrated on Si substrates," *App. Phys. Lett.,* vol. 76, no. 10, pp. 1231-1233, 2000.

[4] A. Nayfeh, C. O. Chui, T. Yonehara and K. C. Saraswat, "A Method to Grow Heteroepitaxial-Ge on Si: Multiple Hydrogen Annealing for Heteroepitaxy (MHAH)," *MRS* Spring 2005 SanFransisco, CA.

[5] V. Chu, J. P. Conde, D. S. Shen, and S.Wagner, "Photocurrent collection in a Schottky barrier on an amorphous silicon-germanium alloy structure with 1.23 eV optical gap," *Appl. Phys. Lett.*, vol. 55, pp. 262–264, 1989.