Modulation Doped Hydrogenated Amorphous Silicon Germanium Superlattice Contacts and Application to Optoelectronic Devices

Bahman Hekmatshoar*, Warren Rieutort-Louis†, Davood Shahrjerdi and Richard Haight

IBM T. J. Watson Research Center
1101 Kitchawan Rd, Yorktown Heights, NY 10598
†Present Address: Princeton University, Department of Electrical Engineering, Olden St, Princeton, NJ 08544

*Email: hekmat@us.ibm.com

Hydrogenated amorphous silicon (a-Si:H) is in widespread production of thin-film transistors and solar cells. While standard thin-film transistors are implemented as n-channel devices with n^+ a-Si:H source/drain contacts, p^+ a-Si:H contacts are required for solar cells and other bipolar devices. The efficiency of p-type doping in a-Si:H is fundamentally limited due to the large valence band tail density of states, thus limiting the device performance.

In one example, Fig. 1 illustrates the schematic energy band diagram of the back contact of a heterojunction solar cell with a p-type crystalline Si (c-Si) absorption layer and a p^+ a-Si:H/i a-Si:H back-surface-field stack, in which the thin intrinsic (i) a-Si:H layer serves to passivate the surface of the c-Si substrate. A high activated doping is desired in the p^+ a-Si:H layer to create a sufficiently large electric field for repelling the minority electrons from the surface of the c-Si substrate. In addition, the p^+ a-Si:H layer must be sufficiently thin (while maintaining a minimum thickness to avoid full depletion) to allow efficient tunneling of the majority holes towards the back contact. Although it is generally possible to improve the doping efficiency by increasing the crystalline portion of the film, the growth of thin layers of nanocrystalline or microcrystalline Si without an amorphous transition layer is challenging. Furthermore, the growth of such layers typically requires high amounts of hydrogen dilution which may degrade the underlying i a-Si:H passivation layer.

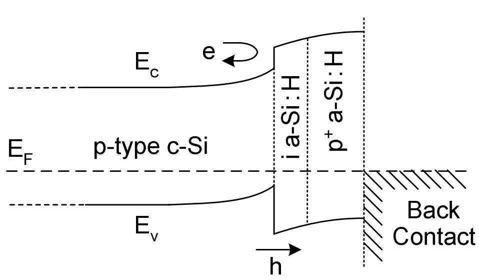

Fig. 1. The schematic energy band diagram of the back-surface-field contact of a heterojunction solar cell with p-type c-Si substrate in thermal equilibrium. The back-surface-field stack serves to repel the minority electrons from the c-Si surface thus reducing electron-hole recombination while allowing the transport of the majority holes to the back contact.

In another example, Fig. 2 illustrates the schematic energy band diagram of the back contact of an a-Si:H based photoreceptor. A p^+ a-Si:H blocking layer is used to block the injection of electrons from the metal contact into the p^- a-Si:H photoreceptive layer thus reducing the dark discharge of the photoreceptor. A highly doped p^+ a-Si:H blocking layer is desired to effectively block the injected electrons by annihilating them through recombination in the p^+ a-Si:H layer. While a thicker p^+ a-Si:H annihilates a larger number of electrons injected from the metal contact, it generates a larger number of electrons by defect-assisted thermal generation of electron-hole pairs. The generated electrons may be injected into the photoreceptive layer and contribute to the dark discharge. Therefore, the low doping efficiency of the p^+ a-Si:H blocking layer cannot be compensated by increasing its thickness.

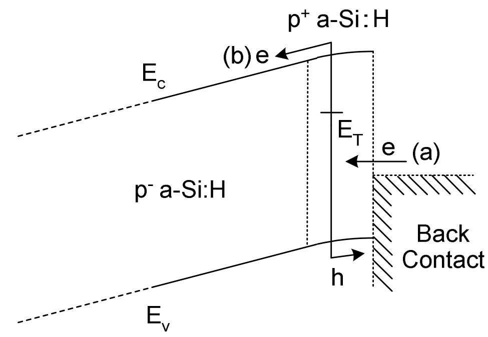

Fig. 2. The schematic energy band diagram of the back contact of an a-Si:H based photoreceptor with a p^+ a-Si:H blocking layer. The blocking layer serves to annihilate the electrons injected from the back contact electrode (a) which would otherwise contribute to the dark discharge of the photoreceptor. However, defect assisted thermal generation of electrons (b) from the blocking layer itself (as illustrated for a trap level at E_T) contributes to the dark discharge.

In this presentation, the modulation doping of hydrogenated amorphous germanium (a-Ge:H) in p^+ doped a-Si:H/a-Ge:H superlattice stacks is investigated from temperature dependence of electrical conductivity, photo-conductance decay measurements and ultraviolet photoemission spectroscopy. We show that a thin layer of a-Ge:H inserted in p^+ a-Si:H can be doped efficiently by transfer of holes from a-Si:H into a-Ge:H and therefore improve the device performance if used as a heterojunction contact or blocking layer. This technique has been used to achieve heterojunction solar cells with p^+ doped a-Si:H/a-Ge:H/a-Si:H back-surface-field stacks with a conversion efficiency of ~ 22% on p-type c-Si substrates [1, 2]. We also show that blocking layers comprised of p^+ a-Si:H/a-Ge:H/a-Si:H stacks can reduce the dark discharge in a-Si:H photoreceptors by a factor of ~10. Similarly, we show a reduction of ~10X in the reverse saturation current of a-Si:H based p-i-n photodetectors using this technique, resulting in an improvement of 10X in the signal-to-noise ratio.

Acknowledgement – The authors gratefully acknowledge Dr. Devendra Sadana and Dr. Ghavam Shahidi of IBM Research for technical discussion and managerial support; and Prof. Sigurd Wagner of Princeton University for allowing the usage of his PECVD facility for this work.

References:

[1] B. Hekmatshoar, D. Shahrjerdi, and D. K. Sadana, "Novel Heterojunction Solar Cells with Conversion Efficiencies Approaching 21% on p-Type Crystalline Silicon Substrates", *IEEE Int. Elect. Dev. Meet*. p. 36.6.1, Dec. 2011

[2] B. Hekmatshoar, D. Shahrjerdi, M. Hopstaken, J. A. Ott and D. K. Sadana, "Characterization of Thin Epitaxial Emitters for High-Efficiency Silicon Heterojunction Solar Cells", *Appl. Phys. Lett*. vol. 101, p. 103906, Sep. 2012