

A CMOS Microdisplay Utilizing Hot Carrier Electroluminescence From Reverse-biased Si PN Junctions

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Abstract The emission of visible light by a monolithically integrated Si p-n junction under reverse bias is presented, and a fully CMOS integrated optical-type fingerprint sensor using Si light emitting devices is achieved.

1. Introduction

Various researchers have highlighted the need for small-dimension light emitters which are compatible with mainstream Si CMOS integrated circuit technology [1]. Recent progress in silicon compatible photonics is driving high density integration of photonic and electronic components manufactured by CMOS-based technology on the same platform [2].

Light emission from silicon devices has previously been realized in reverse-biased Si p-n avalanche structures [3]. It is particularly postulated that light emission occurs from these structures through phonon assisted intra-band and inter-band recombination phenomena [4]. Utilizing current density and surface engineering technology, Snyman et al. have succeeded in realizing a number of practical and utilizable Si light emitting devices (Si-LEDs) utilizing standard CMOS design and processing technology [5]. Several models are presented which postulates that enhanced light emission can be obtained in these devices through carrier energy and carrier momentum engineering [6].

The Si CMOS platform is a viable solution to integrate both, electronic and photonic devices. Significant progress has been made with the potential to move beyond application specific electronic photonic ICs and apply this concept to a more general class of ICs. Because of the ease of integration into CMOS technology, these type of devices show great potential to be integrated into CMOS based optical interconnect,

optical RF connection systems and lab-on chip micro-phonic systems. Although present emission levels are sufficient in order to sustain diverse applications, a higher emission power as associated with these devices is desirable. In this paper, we report on further progresses that have been made with regard to modeling of the physical processes in Si-LEDs and in realizing increases in the optical emission power, as well with regard to higher frequency modulation capability of such devices.

2. Device description and experiments

In this research, two different device structures are hence designed and realized in order to promote and test some of the above hypotheses. A 0.35 micron RF bipolar and TEOS oxide based process having Si-Ge layer capability was used for this purpose. With minor modifications, the process is largely CMOS compatible. Fig. 1 shows schematic diagrams of the cross sectional views of the Si-LED design.

In the first structure, p⁺ and n⁺ regions are created in an elongated columnar region utilizing the n-epi-layer of the process. A p⁺nn⁺ conduction channel device is such created. The device dimension of each sub-section is about 1 micron cube. Appropriate metal contacting is supplied to each regions. The first p⁺n junction is reverse biased such that the depletion region reached through to the second p-n junction. Since the third region was n⁺, the electric field in the lower doped n region is enhanced when the depletion region reaches



through to the n^+ region, and assumes a almost flat E-field profile. This leads to enhanced multiplication and avalanching in the lower doped n region. Energetic electrons and holes under the influence of the high E-field undergo various excitation and recombination processes in this region. Since the middle lowly doped region is of epi material, it can be assumed that the residual defect density in this region is very low, and carrier recombination occurs mainly in a defect free environment. This device was hence nomenclated a “ p^+nn^+ -epi Si Av LED” device.

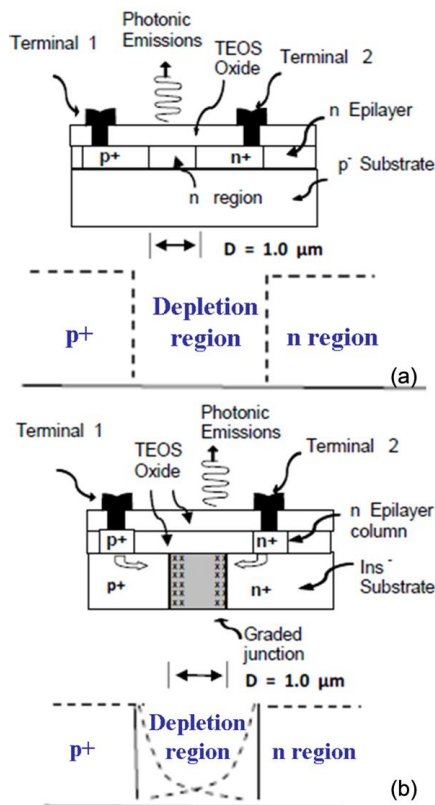


Fig. 1. Device design for controlling impurity and associated defect densities: (a) p^+nn^+ device in epi-layer; (b) Device with graded p^+ and n^+ regions in the substrate. The respective impurity doping profile distributions are indicated in each case.

In the second structure, the impurity profiles are graded with less impurity concentration in the centre middle region. The inter-junction distance was also increased to 1.0 micron. The device were generated in the substrate region below the epi-layer where dopant profiles were much deeper and also subjected to several successive thermal processing procedures. Subsequently, up to 1 micron, graded doping profiles are formed at the edges of these regions; and only some dopant compensation occurred in the center region. A non-linear Gaussian type electric field is hence maintained in the device's centre region. The device was hence nomenclated “ p^+nn^+ graded junction Si Av LED”.

Fig. 2 presents the I - V curves as observed for the various devices. The p^+nn^+ epi-layer device had the lowest operating voltage, while the higher voltage operations of the other two devices are attributed to lower E field and the larger middle traverse regions of these devices, respectively.

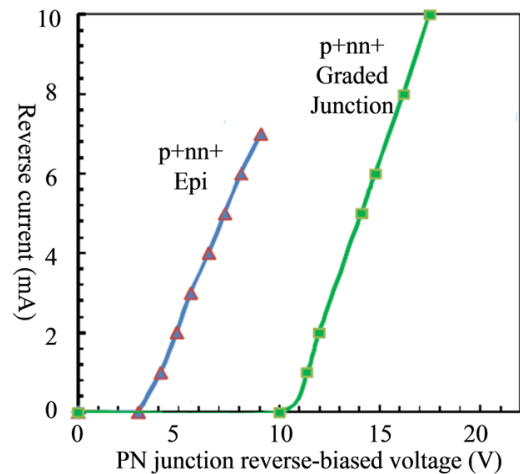


Fig. 2. Experimental results as obtained for p^+nn^+ , p^+n^+ overlap and p^+nn^+ graded junction Si LED devices: I - V curves as measured.

Fig. 3 gives a simple synopsis of the light emission mechanisms in silicon as they occur in a silicon reverse biased p - n junction. Electrons are accelerated in the strong electric field of the junction; the energy gained by the carriers are transferred to the lattice and electron-hole pairs are formed during the subsequent host atom ionization processes. During the subsequent energy relaxation and carrier recombination processes, light is generated in and around the junction region.

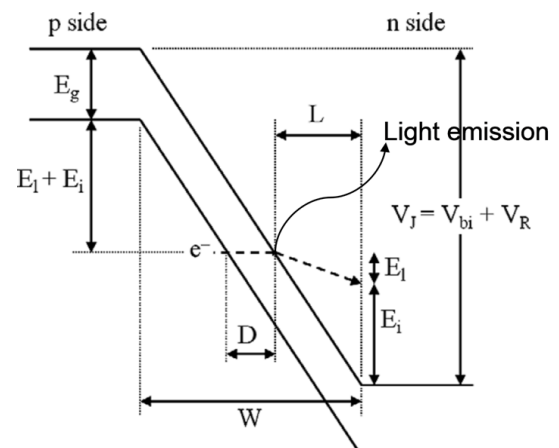


Fig. 3. The energy band diagram of the p - n junction illustrating an electron tunneling from the valence to the conduction band at the electric field peak position, leading hot-carrier induced light emission.

Fig. 4 shows the spectral power densities versus wavelength that is observed for each device. These are

measured with an Anritso MS9710B Spectrum Analyzer with a lensed fiber probe having a numerical aperture of 0.4. Logarithmic vertical scaling is used. Very evident is the predominantly 750 nm and 850 nm emissions for the $p^{+}nn^{+}$ epi-layer device. These emissions corresponds well with 1.8 eV and 1.5 eV emissions. These may correspond with intra-band optical emissions of transition. The 650-nm peak has been generally observed for electron relaxation in n-p junctions⁷, and may be related to the threshold for pair production during ionization of the Si host atoms with electrons (1.8 eV); the secondary peak at 800 nm may be caused by transmission and interference effects due to the thin residual oxide layer on the n^{+} -Si surface⁸.

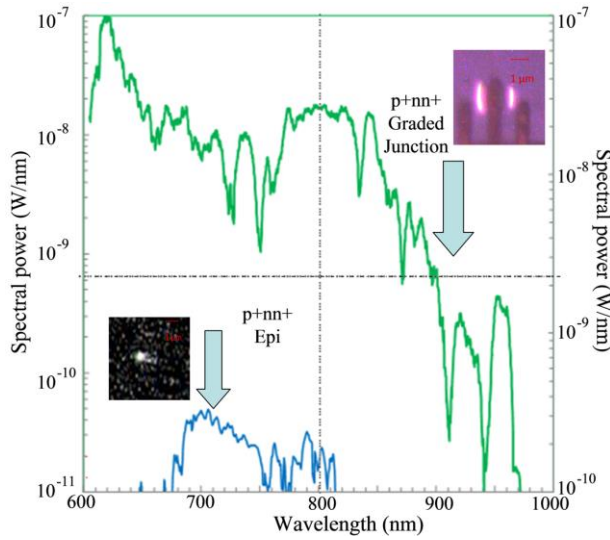


Fig. 4. Normalized electroluminescence spectra of the two types of p-n junctions.

The dominant intraband c-c photon generating process can be either a direct c-c or an indirect phonon assisted (PA) c-c transition. It was found by simulation that the direct c-c radiation dominates at lower photon energies, and the indirect PA c-c radiation dominates at higher energies⁹. A detailed theoretical study was made of the relationship between the kinetic energy of a carrier, the effective carrier temperature, and the corresponding photon distribution assuming an exponential distribution of hot-carriers in the conduction band¹⁰. Therefore, it can be obtained that energy distribution function $f(E_{photon})$ of photon intensity can be given by

$$f(E_{photon}) \sim \exp\left(-\frac{E_{photon}}{kT_e}\right) \sim \exp\left(-\frac{E_{photon}}{qE_x d}\right) \quad (1)$$

where E_{photon} is the energy of photon and T_e is the effective temperature of hot-carriers.

Also, Eq. (1) presents that the reverse-biased p-n junction depletion region's electric field E_x increases with the photon intensity.

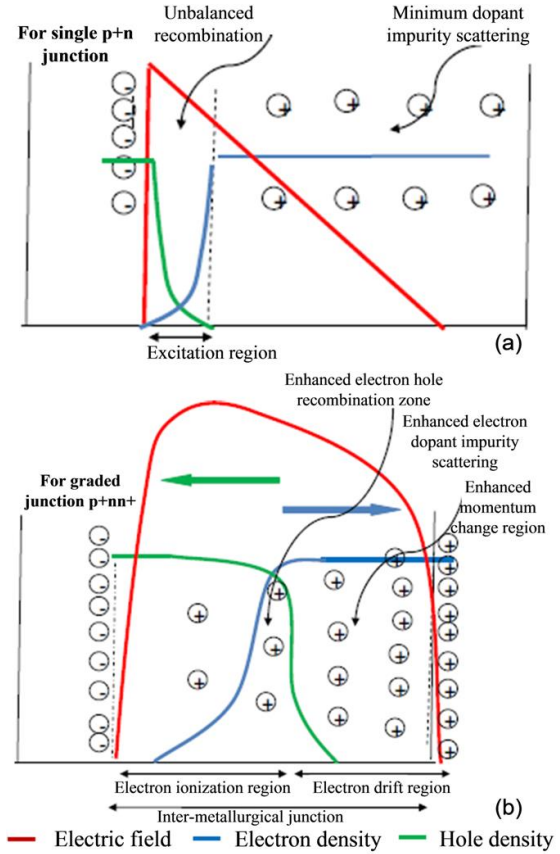


Fig. 5. Device modeling for two types of $p^{+}n$ Si Av LEDs. (a) Electric field and carrier density profiles for a single junction abrupt doping profile $p^{+}n$ abrupt junction Si Av LED, showing unbalanced and minimized scattering of carriers by impurity centers. (b) Electric field and carrier density profiles for a graded junction $p^{+}nn^{+}$ Si Av LED showing balanced and maximized scattering of diffusing electrons by positively charged dopant impurity atoms.

The electric field distribution for the two types of p-n junction-based device structures is shown in Fig. 5, and this scenario leads to the enhanced photonic emission in the visible as well as in the near infrared wavelength regions as observed in Fig. 4. Furthermore, the broad spectrum is attributed to the defects and states at or near the Si/SiO₂ interface¹¹.

3. Conclusion

CMOS based light sources have been shown to exhibit illumination levels that can be utilized in micro displays. In addition to the hot electron electroluminescence in Si, the spectral characteristics and the light intensity highly depend on the specific structure and materials, as well as processing technique.

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