Visible light emission from reverse-biased silicon nanometer-scale diode-antifuses

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Abstract— **Silicon nanometer-scale diodes have been fabricated to emit light in the visible range at low power consumption. Such structures are candidates for emitter elements in Si-based optical interconnect schemes. Spectral measurements of Electroluminescence (EL) on the reverse-biased nanometer-scale diodes brought into breakdown have been carried out over the photon energy range of 1.4-2.8 eV. Previously proposed mechanisms for avalanche emission from conventional silicon p-n junctions are discussed in order to understand the origin of the emission. Also the stability of the diodes has been tested. Results indicate that our nanometer-scale diodes are basically high quality devices. Furthermore due to the nanometer-scale dimensions, very high electrical fields and current densities are possible at low power consumption. This makes these diodes an excellent candidate to be utilized as a light source in Si-based sensors and actuator applications.**

Keywords— **Electroluminescence, Si-LED, Si light source, nanometer-scale diodes.**

I. INTRODUCTION

THERE is a need for an efficient Si-based on-chip light source for application in integrated optics as well as optical sensors. The integration of silicon light sources with silicon microelectronics could lead to inexpensive optical displays and offer the potential for VLSI-compatible optical interconnect systems, enabling next generation technologies. Such light sources should be low power and small. One of the major problems faced with Si-based optoelectronic technology is the fabrication of an efficient light source in silicon. It is well established that silicon p-n junctions biased in avalanche breakdown emit visible light [1], [2], [3], [4]. However, these devices require high power and light is emitted over a relatively large area and is therefore difficult to be collected. In this work we report spectral measurements of the electroluminescence of nanometer-scale diodes. The fabrication of these nanometer-scale diodes is based on the formation of a small antifuse [5] with the properties of a diode by gate oxide breakdown in n^+-poly - oxide - p-substrate MOS capacitors. For this reason we will call our devices diode-antifuses [6]. Due to their small dimensions they act as an extreme point source at low power consumption, making them very suitable to be integrated for application in on-chip optical sensors. Previously proposed mechanisms as responsible of light emission in conventionally fabricated reverse-biased diodes are presented and discussed to explain the mechanisms responsible for the emitted light in our devices.

II. PRINCIPLE OF OPERATION

The diode-antifuse is an intentionally formed gate-substrate link in n^+-poly - oxide - p-substrate MOS capacitors. The devices are created (programmed) by controlled electrical breakdown of the gate oxide layer. Breakdown of the gate oxide is achieved by forcing a limited current $-I_p$ (gate injection) through the MOS capacitor, inducing tunnel current until breakdown occurs, see Fig. 1. To ensure controlled breakdown a 1MΩ resistance was placed close to a probe tip to limit the discharge of parasitic capacitances in the wafer measurement set-up. After breakdown a small electrically conductive link connecting the top and bottom electrodes is formed in the dielectric layer with the properties of a diode. The size of the conductive link can be strongly influenced by the electrical power ($V_p \cdot I_p$) used during programming and is typically between 5 nm and 100 nm, see Fig. 2. Therefore nano-scale diodes can be formed easily and they have already been exploited in low-cost Diode Programmable Read Only Memories (DPROMs) [7].

III. EXPERIMENTAL PROCEDURES

A schematic cross section of the structures studied is depicted in Fig. 1. The MOS capacitors consisted of a 60 nm thick field oxide isolation, 10^{19} cm^{-3} or 10^{16} cm^{-3} p-type doped substrate, 6 or 8 nm gate oxide grown in diluted oxygen at 900°C and a 300 nm thick phosphorus implanted LPCVD poly-silicon gate ($8 \cdot 10^{15}$ cm^{-2}, 50 keV) followed by a 30 min, 900°C furnace anneal. Besides the small-area cells (10 μm × 10

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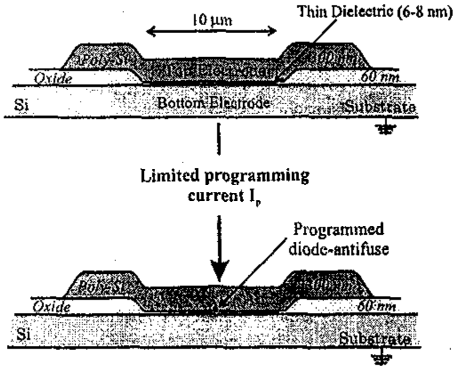

Fig. 1. Cross section of the MOS structure. Programming of the devices is done by forcing a limited current through the capacitor until breakdown occurs, resulting in the formation of a diode-antifuse.

μm), large-area capacitors (100 μm × 100 μm) were also fabricated in this experiment to study the defect density and the reliability of the gate oxide. The experimental setup shown in Fig. 3 is used to record the emission spectrum of the diode-antifuses. This setup is described in more detail in Ref [8]. After the light has been picked up by the microscope, it is fed through a prism and a focusing lens. After this the projected image of the spectrum is amplified by a photo-cathode, a multi-channel plate and projected onto a phosphor screen in front of a CCD imager chip. The spectral range of the whole system is mainly determined by the photo cathode material (S25) and restricted to the energy range of about 1.38 eV to 3.25 eV (900 - 380 nm).

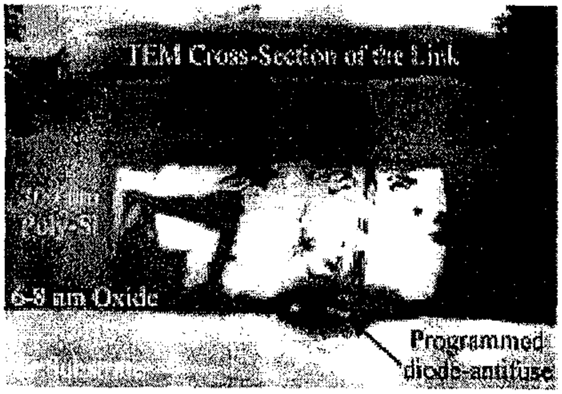

Fig. 2. Transmission Electron Microscope(TEM) of a programmed diode-antifuse. The size of the link is about 10 nm.

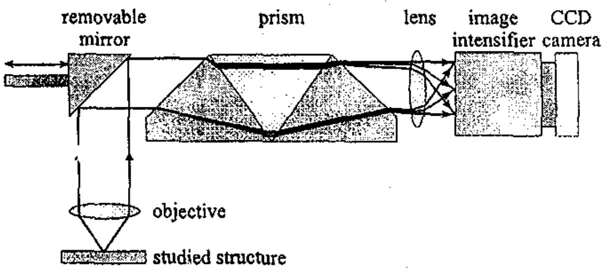

Fig. 3. Experimental setup for the light emission spectra measurements, including microscope and removable mirror. The right side arm contains the prism and image-intensifier for the spectral recording.

IV. EXPERIMENTAL RESULTS

Fig. 4 shows the current-voltage characteristics of the diode-antifuses programmed at I_p=-10 mA. The low leakage current of the programmed diode-antifuse with a substrate doping of $N_{sub}=10^{16}$ cm^{-3} (Fig. 4, dashed line) indicates that it is basically a high quality device. However, to obtain light emission at low power, breakdown at a low voltage is needed. This is achieved by using a highly doped substrate $N_{sub}=10^{19}$ cm^{-3}, which lowers the breakdown voltage (V_b) down to 5.3 V (Fig. 4, solid line).

From the forward characteristics it is possible to extract the junction quality factor (n=1.2 (low N_{sub}) and n=2.2 (high N_{sub})). This low value of the ideality factor reflects the good quality of the junction.
Light emission measurements were performed on the diode-antifuses with a high substrate doping, with the diode-antifuses reverse biased just above V_b. The emission spectrum measured at room temperature, for different reverse currents $+I_r$ is shown in Fig. 5. The periodic patterns observed in the EL spectra are independent of the current and oxide thickness and are caused by the interference of the reflected light at the surface and the bottom of the n^+-polysilicon gate. The spectrum shape does not depend on the reverse current, since the steady-state junction electric field is always at the breakdown value. This means that the carrier effective temperature T_e is expected to stay almost the same.

Fig. 6 shows the normalized spectrum at I_r=1 mA corrected for the self absorption of the polysilicon layer [9]. Also in Fig. 6 is the calculated interference pattern for a 300 nm poly-Si layer [10], [11]. From this it can be concluded that the interference model match the observed peaks in the measured spectrum, indicating that the periodic patterns are caused by interference of the light in the poly-Si layer.

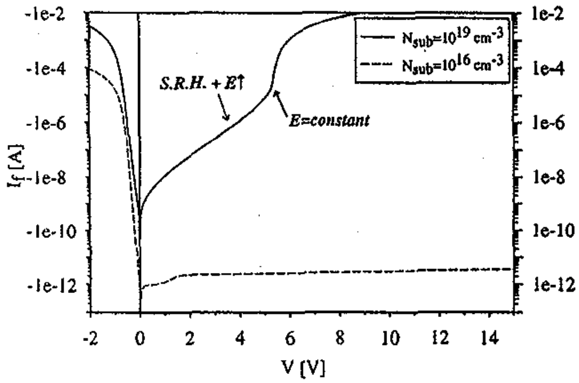

Fig. 4. IV characteristics of the diode-antifuses, programmed at I_p=-10 mA, for two different substrate doping $N_{sub}=10^{16}$ cm^{-3}(dashed line) and $N_{sub}=10^{19}$ cm^{-3}(solid line).

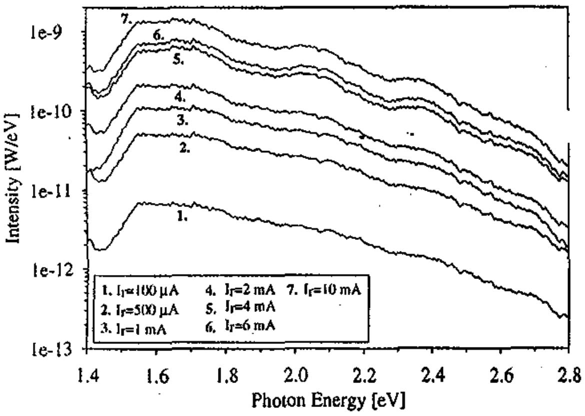

Fig. 5. Emission spectra of the diode-antifuses, measured at room temperature with the diodes biased in breakdown at different reverse currents I_r.

V. Discussion

The experimental spectra from our diode-antifuses show a decrease of intensity below 1.6 eV. They are similar as those reported from conventionally fabricated avalanche silicon p-n junctions. However a wide variety of results are reported in the literature showing a decrease of intensity at different energy positions below 2.0 eV. Chynoweth *et al.* [2] show a spectral intensity increasing over the infrared region. Newman's data [1] exhibit a spectral peak at about 2.0 eV. Deboy *et al.* [12] observe a maximum at 1.8 eV and Haecker [3] reports a decrease in intensity below 0.8 eV.

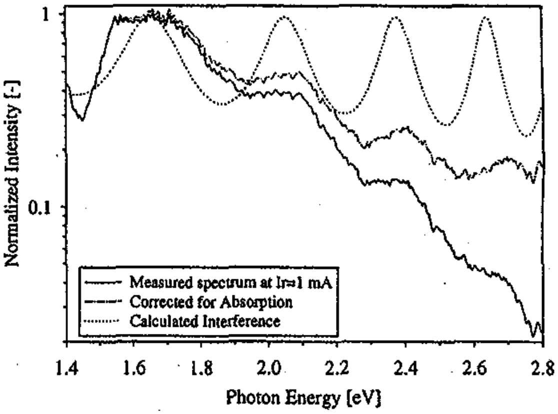

Fig. 6. Normalized emission spectrum measured at I_r=1 mA, corrected for the self-absorption inside the polysilicon layer. Solid line represents the measurement, Dashed line is corrected for the poly-Si self-absorption and the dotted line is the calculated interference of the 300 nm poly-Si layer.

Several attempts have been made to understand the origin of the emitted light [3], [13], [14], [15] and up till now the most important mechanisms proposed in the literature to explain the origin of the emitted light are (see also Fig. 7.) :

1. *interband transition between hot electrons in the conduction band and hot holes in the light hole band* [2]
2. *intraband transition of hot holes between the light and heavy mass valence bands* [3]
3. *bremsstrahlung radiation due to scattering of the hot electrons by charged Coulombic centers* [14]
4. *indirect recombination of electrons and holes under high-field conditions* [15]

These published theories and explanations typically fit at least some of the measured data, but are generally unable to explain the variety of results reported in the literature.

Wolff [13] attributes emission in germanium to direct interband transitions involving holes near k=0 (1). Interband processes cannot produce photons with subbandgap energies. Wolff proposes intraband hole transitions near k=0 to explain low energy spectra, but cannot fit most measured spectra below 2.0 eV.

Chynoweth *et al.* [2] associate emission below 2.3 eV with intraband transitions. Figielski *et al.* [16] propose intraband transitions, specifically bremsstrahlung of hot carriers at charge centers (2). The response of this mechanism however is monotonic and cannot explain the observed spectral peaks.

Haecker [3] proposes that intraband transitions of hot holes between light and heavy mass bands reduce the spectral intensity at low energies (3). The response of Haecker's mechanism peaks in the infrared and is monotonic in the visible. Moreover, intraband hole transitions cannot produce observed intensities of visible photons, and therefore cannot fit the majority of reported spectra. Gautam *et al.* [15] propose the mechanism of indirect interband with phonon-assisted as a responsible of the light (4). This mechanism can explain the observed decrease in intensity below 1.6 eV in the spectrum of our devices.

Using Gautam's approach, differences in spectra measured by different researchers can be attributed to different values of electrical field intensity in the varieties of samples and structures used by experimenters [17]. For our devices a lattice silicon temperature of about 280°C and an electron temperature between T_e=3000 and 4000 K is found, which were also suggested in the case of avalanche p-n junctions [18].

The experimental spectra of our diode-antifuses can be fit by a combined theory involving direct interband model for higher energies, bremsstrahlung for intermediate energies, and indirect interband with phonon-assisted model for low energy part. Results of this will be presented in more detail in another paper [19].

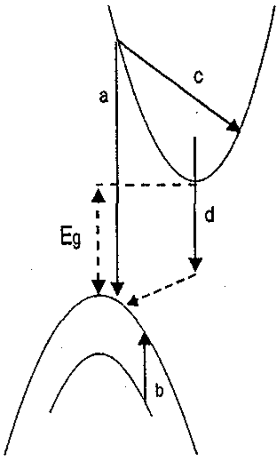

Fig. 7. Silicon band structure model. The arrows represent: a) direct interband recombination, b) intraband hole transitions, c) bremsstrahlung, d) indirect interband recombination.

From Fig. 6 the external power efficiency (PE) has also been evaluated by comparing the measured optical power with the driving electrical power. This leads to a PE of approximately $2.0\cdot10^{-6}$%. This value seems to be low, but it should be noted that the power efficiency is only calculated for the energy range of 1.4 - 2.8 eV and only a small fraction of the emitted light is collected. On the other hand, the power per unit area is high due to the nanometer-scale dimensions of the diode-antifuse and is in the range of 0.1-10 W/cm^2.

VI. Reliability aspects

The stability of the diode-antifuses has been tested over more than one week of continuous operation. A constant current of I_r=$0.5\cdot|I_p|$ was passed through the diode-antifuse while the voltage across the diode-antifuse was monitored. Fig. 7 is a plot of the monitored voltage across the diode-antifuse as a function of the stress time. No significant degradation has been observed, from which it can be concluded that the diode-antifuse is a reliable device. This is in agreement with the already known high reliability data of Si-based antifuses [5].

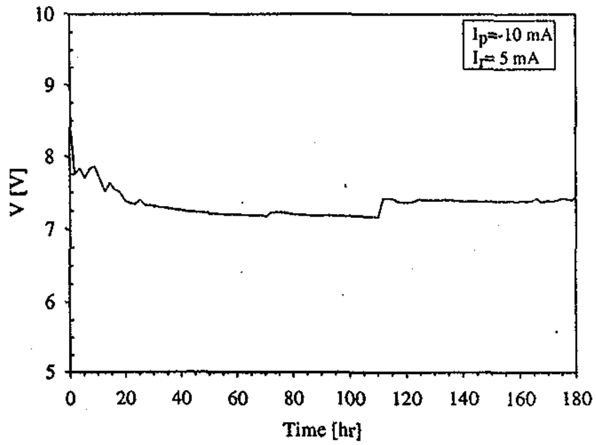

Fig. 8. Voltage across the diode-antifuse as a function of the stress time for a reverse current of I_r=5 mA. The diode-antifuse was programmed at I_p=-10 mA.

VII. Conclusions

We carefully measured the electroluminescence of reverse-biased silicon nanometer-scale diode-antifuses brought in breakdown. We believe that the mechanisms already proposed for avalanche emission from conventionally fabricated p-n junctions, namely direct interband, bremstrahlung and indirect interband with phonon-assisted can also be used to explain the origin of the emitted light from our devices. The external power efficiency has been calculated to be PE=$2.0\cdot10^{-6}$%. The power per unit area is high due to the nanometer-scale dimensions of the diodes and is in the range of 0.1-10 W/cm^2. The stability of the diode-antifuses has been tested, from which it can be concluded that the diode-antifuse is a reliable device.

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