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1998 J. Phys.: Condens. Matter 10 L717

(http://iopscience.iop.org/0953-8984/10/44/001)

J. Phys.: Condens. Matter **10** (1998) L717–L721. Printed in the UK PII: S0953-8984(98)97598-1

LETTER TO THE EDITOR

Electroluminescence from Au/native silicon oxide layer/p^+-Si and Au/native silicon oxide layer/n^+-Si structures under reverse biases

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Received 15 September 1998

Abstract. Electroluminescence (EL) from an Au/native silicon oxide layer (NSOL)/p^+-Si structure and an Au/NSOL/n^+-Si structure has been observed and their EL characteristics have been studied comparatively with those from an Au/NSOL/p-Si structure. The Au/NSOL/p-Si structure emits red light only when a forward bias larger than 3 V is applied, while no light emission can be observed under reverse biases. However, the Au/NSOL/p^+-Si structure or the Au/NSOL/n^+-Si structure emits red light when the applied reverse bias is greater than a critical value around 3 V, while no light emission can be observed under forward biases. It is suggested that for EL from the Au/NSOL/p^+-Si and Au/NSOL/n^+-Si structures under reverse biases, electrons and holes which are generated in the NSOLs by impact ionization in breakdown states radiatively recombine via the luminescence centres in the NSOL to emit light.

Electroluminescence (EL) from many silicon-based systems including porous silicon, native silicon oxide layers (NSOLs), and Si-rich silicon oxide films on Si substrates have been reported [1–12]. The pioneer work on EL from Si-rich SiO_2 was reported by DiMaria *et al* in 1984 [1]. They fabricated an Au/SiO_2 (500 Å)/Si-rich SiO_2 films (200 Å)/n-Si structure using the chemical vapour deposition technique. After annealing at 1000 °C in a N_2 ambient, semitransparent metal films were evaporated onto the Si-rich SiO_2 films. They observed visible EL under a forward bias greater than 15 V in the structure, and attributed the light emission to band–band recombination of electron–hole pairs in nanometre silicon particles. In our previous works, we reported visible EL from two types of silicon oxide structure under forward biases: (1) Au/NSOL/p-Si structure [5, 6], and (2) Au/extra-thin Si-rich silicon oxide film/p-Si structure [8] with the films deposited by magnetron sputtering. Different from DiMaria *et al*'s experiment in [1], we used p-type Si substrates instead of n-type Si substrates and EL could be observed from the structures without annealing under a forward bias larger than 3 V [5, 6] or 4 V [8]. Based on these works, we proposed that EL originates from the radiative recombination of electron–hole pairs via the luminescence centres (defects and impurities) in silicon oxide rather than via nanometre Si particles in silicon oxide. In this paper, we report visible EL from both an Au/NSOL/p^+-Si structure and an Au/NSOL/n^+-Si structure under reverse biases and study comparatively with visible EL from the Au/NSOL/p-Si structure under forward biases.

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The substrates used in this experiment were (100) oriented, $\sim 10^{-2}$ Ω cm p^+-type, $\sim 10^{-2}$ Ω cm n^+-type, and 8–11 Ω cm p-type Si wafers. First, all the Si wafers were cleaned carefully and ohmic contacts on the back sides were formed by evaporating thin Al films and alloying them at 540 °C for 7 min. Then semitransparent Au films (10–20 nm) were evaporated directly onto the polished sides of p^+-type, n^+-type and p-type Si wafers to form Au/NSOL/p-Si, Au/NSOL/p^+-Si, and Au/NSOL/n^+-Si structures, respectively. Before evaporation, the NSOLs on the p^+-type, n^+-type and p-type Si wafers are measured by ellipsometry to be around 3.0 nm, 2.5 nm, and 3.0 nm, respectively. The diameters of all the active cells are 3 mm.

The current–voltage (I–V) characteristics of an Au/NSOL/p-Si structure, an Au/NSOL/p^+-Si structure, and an Au/NSOL/n^+-Si structure, are shown in figure 1. The Au/NSOL/p-Si structure has quite good rectifying behaviour and its breakdown voltage is larger than 10 V, while the Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure have relatively poor rectifying characteristics with rather low breakdown voltages around 3 V.

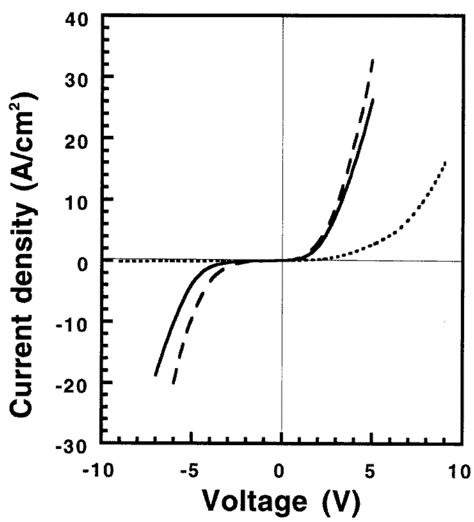
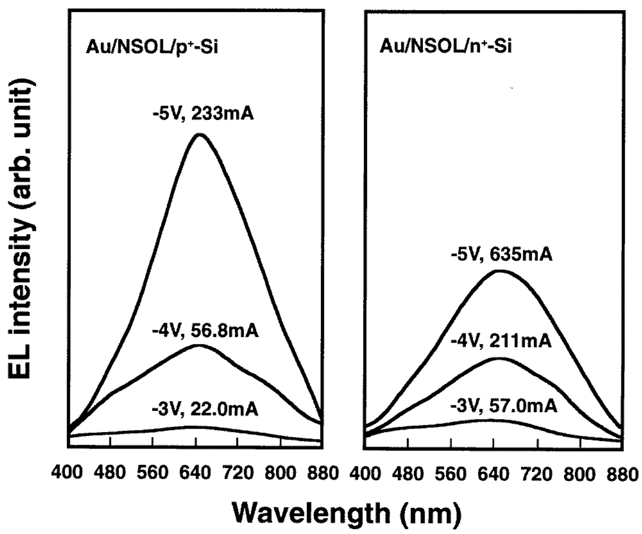


Figure 1. I–V characteristics at room temperature of an Au/NSOL/p-Si structure (dotted line), of an Au/NSOL/p^+-Si structure (solid line), and of an Au/NSOL/n^+-Si structure (dashed line).

For the Au/NSOL/p-Si structure, visible EL can be observed under forward biases (a positive voltage is applied to the p-Si substrate) greater than 3 V, while no EL can be measured under reverse biases. However, for both the Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure, EL can only be observed when they break down under reverse biases. For the Au/NSOL/p^+-Si structure, a reverse bias means a positive voltage is applied to the semitransparent Au electrode; while for the Au/NSOL/n^+-Si structure, a reverse bias means a positive voltage is applied to the n^+-type Si substrate. Moreover, for the Au/NSOL/p-Si structure, visible EL was observed uniformly on the cell; while for the Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure, fibrillar light emission was observed under a microscope.

Figures 2(a) and 2(b) show, respectively, EL spectra from an Au/NSOL/p^+-Si structure and from an Au/NSOL/n^+-Si structure under reverse biases of 3 V, 4 V, and 5 V. The current in the former structure is lower than that in the latter structure under each reverse bias and EL intensity for the Au/NSOL/p$^+$-Si structure increases faster than that for the Au/NSOL/n$^+$-Si structure with increasing reverse bias. Figure 3 shows EL spectra of an Au/NSOL/p-Si structure under forward biases of 3, 4, 5, 6, 7 and 8 V. Comparing figure 2 with figure 3, it can be seen that for all three types of structure, the EL spectra show nearly the same asymmetric shape and each spectrum has a peak around 640–660 nm, which shows no evident shift with increasing bias and current, i.e., EL spectra depend hardly at all on the temperature of the active region of the structure studied.



(a) (b)

Figure 2. EL spectra from an Au/NSOL/p$^+$-Si structure (a) and those from an Au/NSOL/n$^+$-Si structure (b), under reverse biases of 3, 4 and 5 V.

If the NSOLs on the p-Si, p$^+$-Si, and n$^+$-Si substrates were removed thoroughly by HF before the semitransparent Au films were evaporated, Au/p-Si, Au/p$^+$-Si, and Au/n$^+$-Si structures do not show any EL under either forward or reverse bias.

Generally speaking, for metal–insulator–semiconductor structures, EL is a result of bipolar injection of electrons and holes. Therefore, for the metal and the semiconductor, sufficient electrons and sufficient holes are necessary for EL [11]. For the Au/NSOL/p-Si structure under forward biases, this requirement is fulfilled well. When the positive voltage is applied to the Si substrate of the Au/NSOL/p-Si structure, the Fermi energy level of the electrons in the Au film is higher than that in the p-Si substrate and their difference divided by $|q|$ (q is the electron charge) is equal to the forward bias applied if the voltage across the p-Si substrate is neglected. So, electrons from the metal electrode and holes from the p-Si substrate, respectively, tunnel into the dielectric films and radiatively recombine via luminescence centres there. If there are nanometre Si particles in the NSOL, the electrons and holes may tunnel more easily because the tunnelling distances are reduced and the quantum confinement effect in the particles may affect the energies and the relaxation processes of the electrons and holes and thus affect the tunnelling processes. However, for both the Au/NSOL/p$^+$-Si structure and the Au/NSOL/n$^+$-Si structure under reverse biases, usually insufficient electrons and holes can be provided. For example, for the Au/NSOL/p$^+$-Si structure under reverse biases, there are neither sufficient holes injecting from the Au

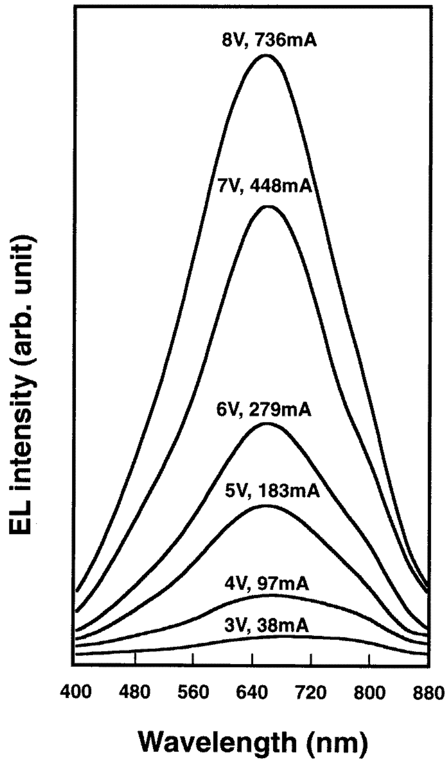


Figure 3. EL spectra from an Au/NSOL/p-Si structure under forward biases of 3, 4, 5, 6, 7 and 8 V.

electrode nor sufficient electrons injecting from the p^+-Si substrate. Therefore, the fact that no EL can be seen from both the two types of structure before breakdown can be easily explained. The Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure break down under reverse biases of only 3–4 V as shown in figure 1. Under these conditions the electric fields in the NSOLs are very high, e.g., for a NSOL with a thickness of 3 nm under a reverse bias of 3 V the electric field is around 1.0×10^7 V cm^{-1}, which is just equal to the breakdown field of SiO_2 [13]. From figure 2, it can be seen that for the two structures the EL starts at reverse biases of 3–4 volts, too. The above experimental facts indicate that the Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure are already in the breakdown states when they emit light under a reverse bias. We suggest an EL mechanism model for the above structures as follows: When a reverse bias is applied and electric field is strong enough in the NSOL, avalanche breakdown occurs, and many electrons and holes are generated in the NSOL by impact ionization. The generated electrons and holes drift in opposite directions under the electric field and radiatively recombine via the luminescence centres in the NSOL. Although the processes of carriers' generation and transportation for the Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure under reverse biases are quite different from that for the Au/NSOL/p-Si structure under forward biases, in both cases radiative recombination is mainly via luminescence centres in the NSOLs. Otherwise, the experimental facts that the EL spectra from the Au/NSOL/p^+-Si structure and the Au/NSOL/n^+-Si structure under reverse biases and those from the Au/NSOL/p-Si structure under forward biases have very similar shapes, and their EL peaks locate at almost the same position cannot be easily realized.

The reasons why non-uniform EL was observed for the Au/NSOL/p^+-Si and Au/NSOL/n^+-Si structures are due to the non-uniformity in thickness as well as stoichiometry of the NSOLs, which results in local avalanche breakdown in the active region of the NSOLs.

In conclusion, EL from the Au/NSOL/p^+-Si and Au/NSOL/n^+-Si structures and that from the Au/NSOL/p-Si structure were studied comparatively. For the Au/NSOL/p-Si structure, it emits visible light under only forward biases which is attributed to injection of electrons from the Au electrode and holes from the p-Si substrate and electrons and holes recombine radiatively in the luminescence centres in the NSOL. However, for Au/NSOL/p^+-Si and Au/NSOL/n^+-Si structures, EL can only be observed when the reverse biases applied are larger than certain critical voltages and avalanche breakdown is a prerequisite for EL. Although carriers' transportation in these structures under reverse biases is very different from that of Au/NSOL/p-Si structures under forward biases, the mechanisms of radiative recombination of the carriers in all the structures almost the same, i.e., electron–hole pairs radiatively recombine mainly via the luminescence centres in the NSOLs.

This work has been supported by the National Natural Science Foundation of China and by the State Key Laboratory for Integrated Optoelectronics.

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