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Slow contamination and fast surface state effects SEM studies of Si phototransistors

M. WILSON,* R. OGDEN,† D.B. HOLT
Department of Metallurgy and Materials Science, Imperial College of Science and Technology, London SW7 2BP, UK

The rate of growth of contamination films on the surface of Si phototransistors under examination in a scanning electron microscope was measured by multiple beam interferometry. The contamination film reduced the barrier electron voltaic effect current (i.e. the "EBIC" signal) by 10 to 20% after scanning a single line for an hour. The photovoltaic effect current of the transistors however was reduced by 90% after scanning the whole area of these devices for a few seconds. This is ascribed to the fact that bombardment–induced changes in surface electrical conditions strongly affect the carriers produced near the surface by photons but not the carriers produced at depths up to 2 μm or more by the electron beam.

1. Introduction

An earlier paper [1] on conductive mode scanning electron microscope (SEM) studies of Si phototransistors reported the appearance of lines of contrast on the micrographs that were induced by prolonged scanning of the electron beam over these lines. This beam-induced change in appearance consisted of a local reduction in the charge collection signal, the barrier electron voltaic effect current [2] sometimes referred to as "EBIC" (electron beam induced current). Studies have now been carried out to determine whether this induced contrast arises from contamination or some form of damage or charging.

2. Experimental techniques

The specimens were planar silicon phototransistors produced by the Plessey Co. and similar to those previously studied [1]. In order to induce lines of contrast under standardized conditions all the observations were made with the specimens at room temperature. Lines 0.76 mm long were scanned at a magnification setting of 100× at a beam accelerating potential of 20 kV in a Cambridge Instruments Stereoscan IIA SEM. The beam current and spot size were determined using the method of Joy [3].

The barrier electron voltaic effect current induced by electron bombardment in the base-collector p–n junction was detected by a modular conductive mode detection system shown in Fig. 1, to be described in more detail elsewhere [4]. This can be set so the input impedance is very low so that a short-circuit current from the specimen can be obtained and linearly amplified and monitored via a built-in digital meter. The specimens were connected across the input of the head amplifier of the detection system so that I_{CEO}, the current between the collector and the emitter with the base floating, was obtained. This is an important improvement on the coupling circuit used in previous work of this kind [1, 5, 6]. The latter incorporated a reverse biasing battery together with a condenser and resistance. The condenser provided a.c. coupling so the amplifier differentiated the signal, and the condenser and resistance constituted a high-pass filter, so that the low frequency com-

*Present address: Department of Metallurgy and Science of Materials, University of Oxford, Oxford, UK.
†Present address: Allen Clark Research Centre, The Plessey Co Ltd, Caswell, Towcester, Northants, UK.

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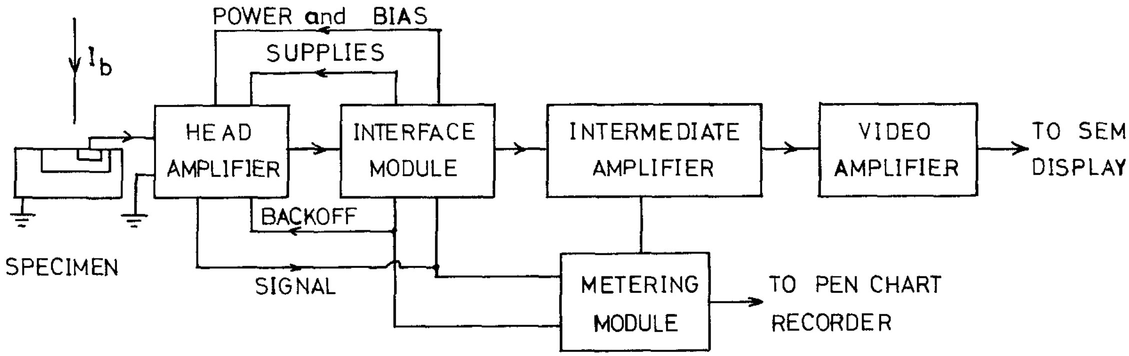

Figure 1 Schematic diagram of the specimen and the modular conductive mode detection system for quantitative SEM observations. I_b is the incident electron beam current. The head amplifier is mounted adjacent to the specimen in the stage of the SEM. All the other modules are mounted in an external rack.

ponents of the signal were attenuated, so quantitative observations were not possible.

Preliminary observations using two-beam Nomarski optical interferometry indicated that films of increasing thickness built up during scanning [7]. Multiple beam interferometry was therefore used to determine the thicknesses of these films.

3. Results and discussion

Examples of lines of contrast induced by line-scanning the beam are shown in Fig. 2. By recording the barrier electron voltaic effect (beve) current while scanning a line crossing one or more such dark lines the percentage reduction in the beve current corresponding to the induced lines was measured. It was found that for constant beam conditions, the deposited film thickness increased linearly with the total time for which the dark line was scanned as shown in Fig. 3. Moreover, the reduction in the beve current was proportional to the thickness of the films measured on the dark lines as shown for example in Fig. 4.

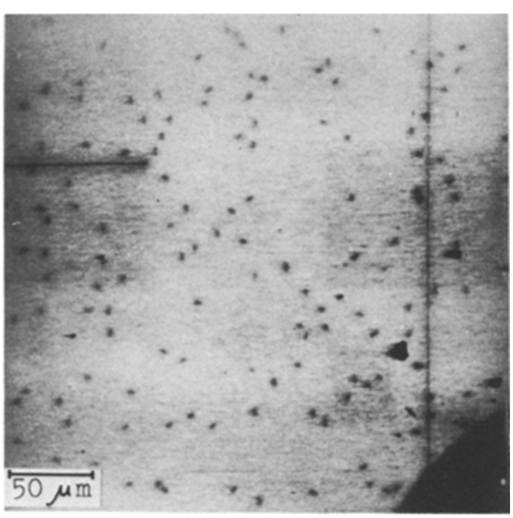

Figure 2 Conductive mode SEM micrograph displaying the barrier electron voltaic effect short-circuit current as video signal. The specimen was under a 5 V reverse bias. A horizontal and a vertical contamination line are visible as well as rectangular contaminated areas.

It is concluded that the induced dark lines on beve SEM micrographs are due to the build-up of carbon contamination films during the prolonged beam irradiation on the following grounds. Firstly, such contamination is well-known to occur in transmission electron microscopes [8] as well as in SEMs [9,10] and the rate of deposition increases linearly with the current density for small densities. It was established in the present work that for a constant total linescan time of 60 min the contamination thickness increased approximately linearly with the current density in the beam [11] whereas it was independent of line scan speed and specimen bias and surface potential. Secondly, it is accepted that the mechanism of contamination is the ionization of absorbed hydrocarbon molecules on the surface by the beam followed by the diffusion over the surface of the resultant free radicals and finally their cross-linkage to produce the polymeric contamination film. The mean free path of surface diffusion at room temperature is of the order of a few μms. It can be seen in Fig. 2 that the dark lines have strips of intermediate darkness on *either* side which are a few μms wide. These are apparently regions in which the diffusing radicals have reacted to produce a contaminant film of lesser thickness than that in the central beam-bombarded line. Thirdly, the linear increase of

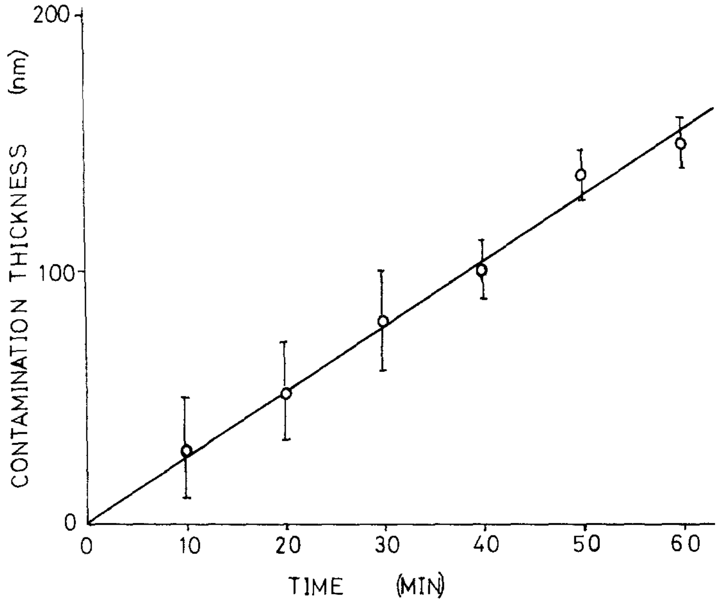

Figure 3 Contamination film thickness versus total time for which the line was scanned. The beam current density was $70.1\,A\,m^{-2}$, the line scan time 20 m sec for a line 0.76 mm long and the beam voltage 20 kV.

film thickness with total bombardment time to be expected on this mechanism of contamination and found for example in Fig. 3, would account for the linear beve current reduction with total bombardment time, observed in a separate series of measurements provided that the reduction increases linearly with film thickness as was actually found to be the case (Fig. 4).

The latter linear dependance can be accounted for since the initial portion of the beam energy loss versus depth of penetration curve is approximately linear [12,13]. However, the reduction of 10 to 20% in the beve current for the addition of a $100\,nm = 0.1\,\mu m$ carbon film is too large to be accounted for by absorption alone. This contamination film is atop a $0.65\,\mu m$ layer of SiO_2 and $2.1\,\mu m$ of Si above the detecting p–n junction. Thus the increase in the depth to the junction is only 3.5%. Since the density of carbon (graphite) is 10 to 20% less than those of Si and silica, the in-

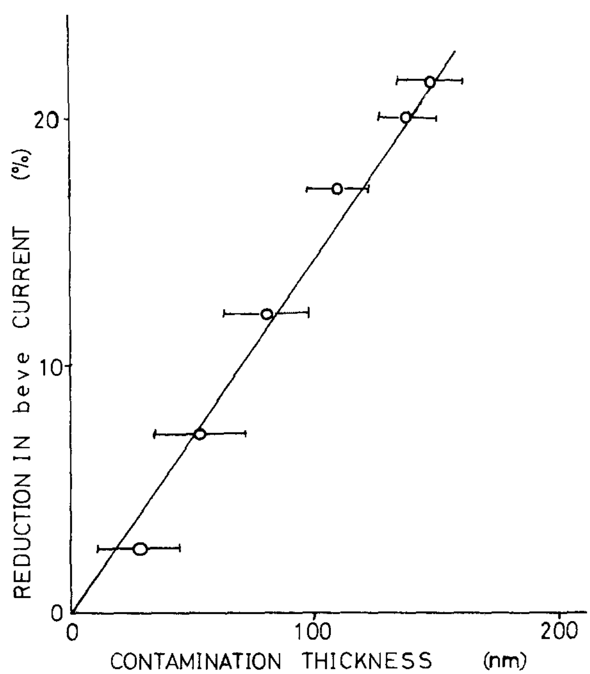

Figure 4 The percentage reduction in the beve current at dark lines versus the thickness of the contamination films on the surface of the lines. These lines were produced by prolonged scanning of the beam with a current density of $70.1\,A\,m^{-2}$ and a line scan time of 20 m sec and a line length of 0.76 mm.

crease in the mass depth of the detecting junction is an even smaller percentage. The large effect of these thin films suggests that mechanisms other than absorption are also important.

The build-up of the contaminant films was slow, taking tens of minutes with scanning lines 0.76 nm long to build up films tens of nm thick and produce a few percent reduction in the beve current.

A much faster change occurred in the photovoltaic response of the transistors. The photocurrent for constant illumination conditions was found to be reduced to about 10% of its initial value by even the briefest examination (for a few seconds) in the SEM [14]. It is thought that the explanation of the latter effect lies in the influence of electron bombardment on surface states and surface charges in the transistors. Electron bombardment is known to produce trapped positive charges in silicon dioxide and to increase the surface states at the silicon–silicon dioxide interface. [15,16]. This will strongly affect the photoresponse since the incident light is absorbed in a thin surface layer on the Si producing hole-electron pairs where the influence of surface conditions is a maxium. Electron bombardment with a 20 kV beam will produce hole-electron pairs at depths of up to 2 μm. This is equal to the depth of the base-collector junction. The beve will consequently be little affected by changes in the surface states and charges even though the barrier photovoltaic effect is virtually eliminated. The time taken to produce saturation charging of the oxide in Si MOSTs was found to be of the order of 1 sec [15] corresponding to the order of the total bombardment time found to minimize the photoresponse in the photo-transistors [14].

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