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A NOVEL METHOD OF SEMICONDUCTOR DEVICE MEASUREMENTS

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I. INTRODUCTION

As semiconductor devices are made smaller and smaller, their electrical evaluation becomes increasingly difficult. This paper described a method of measurement which obviates most mechanical contact with the device surface, which is capable of submicron resolution, and which can determine the relative potential of different areas of the device surface. This method, essentially that of scanning electron microscopy, has been known for many years.[1-6] However, its application to passivated integrated circuits has only recently been described,[7-9] and qualitative results shown in the form of micrographs of the device surface. In this method a very small diameter electron beam is scanned over the surface of an integrated circuit. The resulting secondary electrons are collected and provide a video signal which modulates the intensity of a synchronously scanned cathode-ray tube. Alternatively electron-beam-induced currents and voltages from the integrated circuit itself may be used as a video signal to provide complementary information about the sample being examined. The emphasis of this paper is on electrical signals induced in a semiconductor devices by scanning electron beam bombardment and on certain measurements which may be performed using these electrical signals. In the work reported here the final electron spot diameter at the object was a few tenths of a micron, although spot diameters smaller than a hundred angstrom units have been achieved.[10] In order to achieve such small spot diameters, the beam current must necessarily be small, from 10^{-8} to 10^{-11} amperes in these experiments. The accelerating voltages ranged from 5 to 40 kv, which is far below the threshold values necessary to displace atoms from their correct position in the lattice.[11] Therefore, no Frenkel defects are caused by the electron beam used in these experiments.

II. ELECTRON PENETRATION AND SCATTERING IN SOLIDS.

The penetration and scattering of a monoenergetic beam of electrons incident on a solid target is a complicated problem which has received considerable attention over the past few decades, but has not yet been completely solved. The primary electrons penetrating into the solid may lose energy by exciting individual electrons within the solid to higher energy levels or by ionizing them, and by collective interactions with electrons in the solid which result in plasma oscillations. Electron excitation to higher energy states includes excitation of conduction electrons, excitation of valence electrons into the conduction band, and excitation of electrons in tightly bound atomic shells to unoccupied energy levels in the conduction band. Electrons in the conduction band, valence band, or tightly bound atomic shells can also be excited above the conduction bands—i. e., ionized. Secondary electrons are those electrons which are sufficiently excited to escape the target. Marton[12] has reviewed characteristic energy loss mechanisms, and Pines[13] has reviewed the plasma oscillation theory of energy loss.

Deflection of the penetrating primary electrons through collisions with atomic nuclei, tightly bound atomic electrons, valence, and conduction electrons also occurs.

Collisions of the first two types can lead to large angle deflections, and the cumulative result of all such deflections results in the scattering of the primary electron beam. A certain fraction of the incident electrons are scattered through large angles, and emerge from the target near the point of entry with appreciable energy. These are termed backscattered electrons, and have been studied by Sternglass[14] and Kanter[15] among others. Experimentally, backscattered electrons are generally taken as all secondary electrons emitted by the target with energies above 50 ev, and those secondaries emitted with energies below 50 ev are called "true" secondary electrons. Dekker[16] has recently reviewed the theories of secondary emission. Kanter[17] has shown that the "true" secondary electron yield is proportional to energy dissipation in the surface layer of a target material; he has also presented strong experimental evidence for the Bethe[18] stopping theory, which is widely used to calculate the rate of electron energy loss in solids.

Makhov[19] has derived empirical formulas for the fraction of an electron beam which will penetrate a thin film at a given incident energy, for the range of electrons in solids, etc. His formulas are based on a normalization of experimental results. His work neglects backscattered electrons, and certain of his normalized curves are in slight disagreement with the work of Kanter;[20] however, his range formulas seem to agree well with other published range vs energy curves.[21] Makhov normalized distance in the target to the depth where the intensity has fallen to $1/e$ of its initial value. Most other authors extrapolate the linear portion of the intensity vs penetration distance curve to obtain the practical range, which is then used as the normalizing distance. While there is merit in both choices of normalization, Makhov's value can be converted to the more normal practical range simply by multiplying by a constant factor, 1.44. Figure 1, which shows the range of electrons in silicon, was plotted using Makhov's formula so modified, namely

$$R = 4.9 \times 10^{-3} E_o^{1.65} \quad mg/cm^2 , \qquad (1)$$

where E_o is in kilovolts. The range in centimeters is obtained by dividing R by the density of silicon.

Makhov also argues that the transverse path lengths are related to the range, and for materials of $Z \leq 35$, he finds that the root-mean-square transverse path is approximately 0.7R. While range-energy formulas such as (1) can be expected to hold over only a limited range of voltages[21, 22] they are very useful in this range of energies.

One important mechanism for electron energy loss in semiconductors and insulators is the excitation of valence electrons into the conduction band. Gornyi[23] has observed this as a characteristic energy loss in germanium. Hole-electron pair excitation has been widely used for nuclear particle detectors. This application has been reviewed by W. L. Brown,[24] and more recently by Williams and Webb.[25] When the particle bombarding the semiconductor is in the Mev range, one hole-electron pair is created for approximately each 3.6 ev of energy lost by the incident particle.[26] A. V. Brown[27] has used hole-electron pair excitation by 10-20 kev electrons for high-speed switching of silicon diodes. For his samples and this range of incident energies, he found that approximately 4.7 ev of primary electron energy was required to produce one hole-electron pair.

If this effect is to be utilized for quantitative evaluation and measurements on semiconductor devices, the density of hole-electron pairs created by the electron beam must be known as a function of position relative to the bombarded point on the target surface. From the results of Kanter[17] mentioned above, it can be assumed that the density of the generated pairs is proportional to the energy dissipated/unit volume. This quantity has been studied by Ehrenberg and Franks[28] and more recently by Ehrenberg and King.[29] These authors have used electron-beam-excited luminescence as a measure of energy dissipation, and have mapped equi-intensity contours of luminescent level. Figure 6 in Ehrenberg and King shows that for a range of about 5 microns in KI, the equi-intensity contours are semicircular, centered at the point of impact of the 20 kv primary beam. For higher energies, the contours are elongated, the transverse scatter at the surface being less than at the depth of maximum energy dissipation. By analyzing their photographic results, these authors were able to show that the energy dissipated/unit length increases to a maximum beneath the target surface, and then decreases to zero. As the primary energy increased, the depth beneath the surface where the maximum occured tended to increase also. These results are related to those of Grün,[30] who studied electron beam energy loss in air, and found a universal curve of dissipation vs distance over a wide range of energies, provided the beam energy and penetration distance were properly normalized.

From the above results, it can be concluded that all the incident beam energy delivered to the target is lost within a hemisphere centered at the point of impact and with a radius equal to or less than the maximum range. Most of this energy is dissipated within a smaller concentric hemisphere with a radius equal to or less than the practical range. The exact distribution of energy dissipation does not appear to be known as a function of position in the target at present. For a 10 kv electron beam of 0.1 μ diameter incident on a silicon target, most of the energy will be dissipated within a 1μ hemisphere centered at the point of impact, and the resulting hole-electron pairs will be centered inside this volume. For a 16 kv beam, the hemisphere will be approximately 2μ in radius. Since the resolution which can be achieved in scanning electron micrographs derived from electron-beam-induced voltages and currents will be related to (and generally limited by) this scatter, the distribution of energy dissipation with distance inside the target is of considerable interest for this work. Using specially fabricated targets and techniques related to those discussed in the next section, it may prove possible to measure transverse scatter with more accuracy than has hitherto been possible.

Schumacher and Mitra[31] have used Grün's results to measure the thickness and composition of thin surface films. Their thickness measuring techniques may be extended to the thin layers used in integrated circuits, which are illustrated in the cross-section of Fig. 2. This sample is much more complicated than the simple case of a thin film above a constant substrate. For example, a sufficiently energetic electron beam striking the right-hand aluminum lead above the contact area would penetrate the aluminum, aluminum-silicon alloyed contact, the n+ emitter, p-base, and finally into the n collector region. In some cases, transverse scatter might reduce the accuracy of thickness measurements, and the diffusion of generated hole-electron pairs will always be a source of error, since such diffusion will increase the apparent size of the irradiated region.

The energy needed to produce hole-electron pairs in the highly-doped silicon devices studied here was approximately one pair for each 5 ev of incident energy. Thus a 15 kv electron may excite about three thousand hole-electron pairs in these devices. The minority carriers will diffuse away from the point of excitation, and if they cross a p - n junction before recombining, an electron-beam-induced current (EBI current) across that junction will result. The maximum EBI current will occur when the beam energy is dissipated in or near the depletion layer, and will be a measure of the pair production. The variation of the EBI current with distance of the electron probe from the junction will be a measure of the carrier diffusion length.

In a multi-layer structure such as is shown in Fig. 2, the electrons may not penetrate into the semiconductor region at all, since they may lose all their energy in the aluminum leads or silicon oxide passivation layer. In Fig. 2 three different electron beam energies have been assumed. For the lowest energy chosen, the electron beam penetrates into the semiconductor only in the emitter region. The next higher energy beam penetrates in both the base and the emitter region, and the highest energy chosen penetrates into the semiconductor at all points. However, the amount of energy available for carrier production is different in the various regions; for example, more carriers will be produced near the emitter-base junction in Fig. 2 than near the base-collector junction. Therefore one would expect the EBI current across the emitter-base junction to be larger than the EBI current across the base-collector junction in the absence of applied bias. By properly biasing the collector, base, and emitter junctions, photo-transistor action can be obtained, using the electron beam as a source of carriers (the injected base current).

III. EXPERIMENTAL RESULTS

In this section, experimental results illustrating the penetration and scattering effects are presented as well as measurements on hole-electron pair creation. All these results were obtained with monolithic silicon passivated integrated circuits. While these results are indicative of the sorts of information which may be derived using electron-beam evaluation of integrated circuits, they are not meant to be exhaustive.

Figure 3 shows four micrographs; micrograph (a) was produced by the secondary electron video signal only, when a bias was applied to the collector, base, and emitter of the passivated transistor. The diffusion beneath the masking oxide during fabrication is clearly shown in this micrograph and may be a useful measurement to the device engineer in its own right. Micrograph (b) was obtained by mixing the photovoltage* generated by the scanning electron beam with the secondary electron video signal. Note that the photovoltage darkens the micrograph; the effect is

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*The term photovoltage refers in this section to the voltage generated by EBI currents across a one megohm resistor external to the circuit under test, and connected between the circuit and ground.

more pronounced near the base-emitter junction and the base-collector junction because carriers generated in the depletion layer where the junctions intercept the surface all contribute to the EBI current. Conversely, carriers generated near the center of the base region have to diffuse to the collector-base junction before they can produce an EBI current. This micrograph was taken at a primary beam voltage of 12 kv, and no penetration of the emitter lead is apparent.

Micrographs (c) and (d) are of the same device, taken at beam voltages of 16 and 20 kv, respectively. The peak value of the photovoltage signal was held constant in these comparison micrographs. Note that penetration through the emitter aluminum evaporated lead (see arrow) has started to take place at 16 kv, but no penetration through the emitter region is yet noticeable. At 20 kv, however, appreciable penetration through the emitter region into the base has taken place, causing both the base and the emitter to be darkened.

Transverse penetration of the primary beam, which increases with increasing beam energy, is believed responsible for the increased displacement of the boundary of the photovoltage-darkened zone from the edge of the masking oxide; in micrograph 3(c) taken with a 16 kev electron beam, the darkened photovoltage zone starts approximately 2.5μ from the edge of the silicon oxide mask, whereas in micrograph 3(d), taken with a 20 kev electron beam, the edge of this zone is displaced approximately 4μ from the edge of the masking silicon oxide. Both of these micrographs should be compared with micrograph 3(a), where the junction position is estimated to be approximately 1.5μ from the edge of the masking silicon oxide. These results indicate that the secondary electron video signal produced a higher resolution micrograph for the purpose of locating junctions than does the photovoltage signal; and more quantitative evidence for this conclusion is presented below.

It is also possible to measure these changes quantitatively by recording the video signals; Fig. 4 shows the results of such a quantitative measurement. The device shown in Fig. 4 was studied rather intensively because of the peculiarity located in the base region, which is clearly seen in the micrograph. Both the video signal, consisting of the secondary electron signal mixed with the photovoltage signal, and the photovoltage signal itself were recorded as the electron beam swept horizontally across the line indicated by the arrow in the micrograph. The top trace of the chart recorder shows the video signal, which can be correlated to the intensity of the micrograph, negative-going signals being dark, and positive-going signals being light. The recording shows two successive lines of the scanned raster. The photovoltage is similarly recorded in the bottom trace. Here a positive going signal appears dark on the micrograph and zero signal means no photovoltage is generated. The relative minimum in photovoltage corresponds to the light area in the center of the micrograph.

In Fig. 5 the photovoltage is plotted versus the beam power in microwatts. These data were obtained by setting the beam voltage to a given value, and then changing the beam current and monitoring the variation in the photovoltage with beam current. However, by plotting the points versus beam power, more universal curves are obtained. The 16 kv and the 23. 8 kv curves coincide over much of their length; the 9. 8 kv curve is somewhat lower because at the point where the curve was monitored a substantial fraction of the 9. 8 kv beam energy was dissipated in the oxide covering the junction. The curves saturate at slightly different values of ordinate and abscissa, and at a relatively high value of the photovoltage. The important point about a curve of this sort is not that it is linear (as one would expect), or that it is unique (similar curves have undoubtedly been obtained using light and electrons in the past), but that a curve of this sort can be obtained for any specific point on the surface of an integrated circuit, and therefore quantitative information about any specific point on the circuit can be correlated with the micrographs. This has not been possible in the past.

Figure 6 shows EBI current plotted versus beam power. Again, linear curves were obtained for specific points on a given surface. The lines drawn on this slide are drawn at an accurate 45° angle which corresponds to a linear increase in induced current with beam power. There is a tendency for the experimental data to be slightly below the line at the higher powers, and slightly above the line at the lower powers. No saturation effects are present or expected in these curves.

Figure 7 shows the induced current gain, defined as the induced current crossing a junction divided by the incident electron beam current. When the beam is incident on a collector-base junction covered only by a passivating oxide layer, the collector-oxide curve is obtained. Note that there is a threshold of energy below which the beam does not penetrate the oxide and hole-electron pairs are not generated in the semiconductor material. Above this point, however, the curve increases; initially, as both the number of electrons penetrating through the oxide and their average energy is increasing, the increase is more rapid. At higher voltages, when the average energy of the electrons penetrating the oxide is increasing, but the number is essentially constant, the rate of increase is somewhat less. The circle and triangle curves shown in Fig. 7 were taken from the same chart recording traces at different points on the specimen, beneath an aluminum-base contact and beneath an aluminum-emitter contact respectively. Slightly more beam energy is required to produce a signal beneath the emitter contact than beneath the base contact. These curves also appear linear once the threshold has been passed and may be extrapolated back to the voltage axis. The point where the extrapolated line cuts the beam voltage axis may be used to deduce the thickness of the aluminum and base contacts and the collector oxide in this device following the method of Schumacher and Mitra,[31] and taking into account the discussion of Kanter and Sternglass.[21] Until further calibration measurements are completed, the accuracy possible in determining these thicknesses is only 20 to 30 percent.

The resolution of this technique is limited by the diameter of the scanning electron beam, by scattering effects in the material being examined , and by signal-to-noise considerations.[5] Pease[10] at Cambridge University, has demonstrated electron beam spot diameters less than 100A in diameter, and resolutions approaching 100A using the secondary electron video signal. The location of p-n junctions on bare gallium phosphide to within 0. 2 microns has been demonstrated by Everhart,[32] also using the secondary electron video signal. We have studied the location of p-n junctions covered by passivating layers of silicon oxide, making quantitative measurements on the secondary electron video waveform, and on the electron-beam-induced photovoltage. A typical result is shown in Fig. 8 where the velocity of scan on the specimen surface was approximately 100μ/sec. The recorded curves of video signal vs position as the electron beam is scanned over a reverse-biased junction closely resemble an integrated gaussian curve. Thus the ordinate in Fig. 8 is taken as the distance required for the recorded trace to rise from 0. 16 to 0. 84 of its final value, a distance which corresponds to twice the standard deviation of the gaussian curve. The integrated gaussian interpretation is not so convincing for the photovoltage traces, but has been used as a consistent method of reducing the recorded data. The curves shown here were obtained for a 0. 2 micron thick silicon oxide layer. From similar data on thicker oxide layers, the rise distance of the collected secondary electrons seems almost independent of the oxide thickness. The photovoltage rise-distance increases with increasing oxide thickness, however, although the slope of rise distance vs beam voltage decreases somewhat. It should be emphasized that these data are subject to error, due to the assumptions listed above and to the error inherent in manually reducing the recorded traces to the curves plotted here; for this reason, these conclusions are tentative.

IV. DISCUSSION

A meaningful measurement should not, generally, appreciably perturb the system being observed. Electron beam bombardment will heat semiconductors, whose electrical properties are quite temperature sensitive. It will also generate hole-electron pairs, and thus alter the equilibrium conditions existing before the beam strikes the sample. Since in the work described in section III, the electron beam was always moving across the sample surface, any calculation assuming a stationary beam should lead to pessimistic results in terms of the temperature increase of the sample, and the generated excess minority carrier density. A sample calculation in which a stationary one micro-watt electron beam strikes a silicon wafer, and the power is dissipated within a radius of one micron from the impact point reveal that considerably less than a one degree Centigrade temperature increase should be expected. A similar calculation for generated carrier densities in silicon which assumes a stationary beam and no recombination (the carriers leave the bombarded region by diffusion only) predicts that maximum carrier densities of the order of $10^{14} cm^{-3}$ should be expected. This number is larger than the carrier densities in intrinsic silicon by approximately three orders of magnitude. For doped material, the maximum generated density of minority carriers may be orders of magnitude above the normal minority carrier density, and may approach the majority carrier density.

The integrated circuit is a very complicated structure to understand exactly, consisting as it does of differently doped planar layers of single-crystal silicon (probably having a high density of crystallographic imperfections, such as dislocations[33]). Recombination and trapping centers located in the bulk, at interfaces between different planar regions, and at the device surface will greatly affect the measurements reported in this paper. Alternatively, controlled experiments using electron beams which are pulsed or scanned may provide new information on these topics. Preliminary measurements have shown that a measure of the diffusion length, and thus the carrier lifetime, can be obtained using this technique. Pulse measurements should also lead to a direct measure of carrier lifetime. Factors which complicate these measurements, such as excess charge introduced by the electron beam, possible charging of the passivating oxide layer, and surface contamination, must be assessed, and either eliminated, or taken into account when performing quantitative measurements more sophisticated than those presented here. Clearly, the application of small diameter electron beams to semiconductor device evaluation is in its infancy. While a promising start has been made in qualitative evaluation, much work remains to be done in the area of quantitative evaluation, before unambiguous and reliable measurements are routine. This paper has attempted to provide background information necessary to exploit this technique, as well as to show certain results already obtained by using it.

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FIGURE CAPTIONS

Fig. 1. Range in silicon vs primary beam voltage.

Fig. 2. Cross-sectional schematic of integrated cricuit showing electron penetration.

Fig. 3. (a) Secondary electron video signal;
$V_B = -1v$, $V_c = +2v$, $V_E = 0v$
Beam voltage = 16 kv.
(b) Photovoltage mixed with secondary electron video signal;
V_B = photovoltage, $V_C = +1v$, $V_E = 0$;
Beam voltage = 12 kv.
(c) Conditions as in (b)
Beam voltage = 16 kv.
(d) Conditions as in (b)
Beam voltage = 20 kv.
Scanning electron micrographs of an integrated circuit, illustrating the variation of the photovoltage signal with beam voltage.

Fig. 4. (a) Photovoltage mixed with video signal; collector-emitter bias = 4v. Beam voltage = 16 kv.
(b) Recorded video waveform and photovoltage of (a) at indicated horizontal line.
Scanning electron micrograph and recorded video and photovoltage waveforms, illustrating one method of obtaining permanent quantitative records.

Fig. 5. Photovoltage vs beam power, with beam voltage as a parameter.

Fig. 6. Electron-beam-induced current vs beam power, with beam voltage as a parameter.

Fig. 7. Current gain vs beam voltage at different points on an integrated circuit.

Fig. 8. Rise distance of secondary electron video signal and photovoltage signal of the illustrated test sample vs beam voltage.