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The influence of ion induced damage on lateral charge collection and IBIC image contrast

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High resolution, calibrated ion beam induced charge (IBIC) measurements from integrated circuit test structures have demonstrated that the measured charge collection in a device can exhibit significant change after only a few hundred ions/ μm^2 exposure, which may easily be exceeded in the initial targeting of a structure. For the purposes of determining a circuit's upset immunity or undamaged charge collection characteristics, such behavior must be accounted for in evaluating IBIC measurements. This paper examines the influence of low level, ion induced damage on the magnitude of the measured lateral charge collection and also its resulting impact on IBIC image contrast.

The lateral charge collection process is first modelled by calculating the amount of charge which diffuses to a collecting junction as a function of carrier diffusion length and the distance between the ion strike and junction edge. The effect of accumulated ion induced damage on lateral charge collection is then incorporated in the model as a decrease in the resultant diffusion length. Calibrated IBIC measurements from the drain of a test FET structure are then explained using this predicted behaviour.

Keywords: IBIC microscopy, lateral charge diffusion, ion induced damage, integrated circuit analysis

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1. Introduction

Ion beam induced charge (IBIC) microscopy uses a focused MeV ion beam to generate charge carriers in integrated circuits and semiconductor wafers. The number of these charge carriers produced by each individual ion is measured as a function of the focused beam's position on the sample surface and used to produce a two-dimensional image showing the scanned region's charge collection response. The development of IBIC was motivated by the need for an integrated circuit analysis tool which could show the structure of surface layers and active junctions within an integrated circuit that may be buried many microns deep [1-4]. Unlike electron beam induced current (EBIC) microscopy, in which the significant 'blooming' of the probing electron beam degrades lateral resolution as the beam penetrates into the integrated circuit, the probing beam of ions used in IBIC suffers little blooming and thus maintains good lateral resolution many microns into the sample. Refs. [3,4] discuss the use of different types of ions to enhance or suppress IBIC contrast from the surface layers and depletion layers.

IBIC is also a valuable tool in the field of radiation testing, especially when used in conjunction with single event upset imaging [5,6]. Single event upset imaging directly images those transistor components within an integrated circuit which malfunction when exposed to energetic heavy ions, but it does not provide quantitative information concerning the amount of charge which produced the upset. IBIC provides a quantitative measure of the amount of charge collected at a circuit node when struck by an ion, but does not reflect the effect of the ion strike on the circuit's operation. The use of the two techniques allows specific quantitative knowledge of the upset process within a circuit to be obtained.

IBIC has further been used to produce images of dislocations in relaxed $\text{Si}_{0.85}\text{Ge}_{0.15}/\text{Si}$ layers [7] and in superlattices [8]. IBIC also has been used to investigate the charge collection properties of diamond detectors [9] and solar cells [10]. For a full description of all aspects of the use and applications of IBIC analysis, see Ref. [11].

The large rate of electronic energy loss of a single MeV ion traversing silicon results in the creation of a large number of electron-hole pairs and the resultant charge pulse can usually be detected above the noise level. Thus with IBIC, electron-hole pairs produced by each incident ion are measured as discrete charge pulses. In order to analyse and store the position, time and charge collected from each ion during a scan, the incident beam current is usually set to less than 1 fA ($\sim 6,000$ ions per second). This count rate is dictated by the processing speed of data acquisition systems. However, another reason why it is important to use such low

beam currents for IBIC analysis is the unavoidable presence of ion induced damage. Each incident MeV ion loses, on average, a small amount of energy in collisions with the atomic nuclei of the semiconductor lattice. This nuclear energy loss causes a few atoms to be displaced away from their lattice site [12]. The resultant lattice vacancy and hole act as trapping and recombination centres for subsequent ion induced charge carriers, which leads to a reduction in the measured charge pulse height with cumulative beam dose. As the beam scans across the circuit, it is important to avoid 'overdosing' one transistor component before an adjacent component is measured, otherwise the circuit's charge collection response will be changed non-uniformly from its nominal unexposed behaviour. Since damage effects on IBIC signals have been observed at doses of less than $100 \text{ ions}/\mu\text{m}^2$, extreme care must be taken to avoid introducing damage unevenly across the circuit.

There has been a considerable amount of work carried out on developing the theory and applications of charge collection with EBIC microscopy [13,14]. Donolato [15] has considered in detail the effects of the charge carrier generation volume produced by keV electrons on the resolution attainable for EBIC and also the effect of lateral charge diffusion. For characterising IBIC results a one-dimensional model of the charge pulse height as a function of minority carrier diffusion length, depletion layer and surface layer thicknesses was developed [16]. The effect of ion induced damage occurring during IBIC analysis was incorporated as a reduction in the minority carrier diffusion length caused by the additional ion induced defects. Until recently the effects of lateral charge diffusion on the measured charge pulse height was not considered for IBIC analysis. However, Donolato and Nipoti have recently presented a model for lateral charge diffusion observed from grain boundaries in IBIC images produced using 2 MeV He^+ ions [17]. The effect of the grain boundary was modelled as an increased recombination velocity and calculations were compared with measured IBIC results from polycrystalline silicon.

This paper presents results of calculations in which the previous one-dimensional approach to calculating the IBIC pulse height [16] is extended to two dimensions so that the effects of ion induced damage on lateral charge diffusion can be characterised in a basic manner.

2. Electronic and nuclear energy loss.

Consider the average electronic and nuclear energy losses of two light ions, a 850 keV proton and 14 MeV carbon ion. These incident energies chosen such that the ions have the same range of $12.5 \mu\text{m}$ in silicon. This arbitrary range was chosen to be greater than the typical

surface layer thicknesses of 5–10 μm found on integrated circuits, which is obviously necessary for IBIC analysis.

A 14 MeV carbon ion has a rate of electronic energy loss at the surface of $\sim 1100 \text{ keV}/\mu\text{m}$, compared with $45 \text{ keV}/\mu\text{m}$ for the 850 keV proton. Since the measured charge pulse height is roughly proportional to the rate of electronic energy loss, dE/dz [16], this gives a guide to the relative sizes of IBIC pulses that would be obtained with these ions. Thus if proton induced charge pulses are too small to be detected above the noise level of a device, a heavier ion can be used to produce IBIC images.

However, the average number of defects created by each light ion sharply increases with atomic number. A 14 MeV carbon ion creates, on average, fifty times as many defects as a 850 keV proton, resulting in the onset of damage-related effects at a much lower beam dose. Heavier ions thus produce larger charge pulses but at the expense of poorer IBIC image statistics. The optimum choice of ion is a trade off between these two opposing requirements. Ref. [11] discusses other aspects associated with the choice of the optimum beam type and energy.

3. Calculated effects of lateral charge diffusion.

Fig. 1 shows the geometry used to calculate the effect of lateral charge diffusion on the charge pulse height. The lateral distance away from the edge of the very thin collecting junction at which the ion hits is x and the depth along the ion trajectory at which carriers are generated is z . The number of carriers which diffuse to the edges of the junction is calculated by integrating the rate of charge carrier generation rate over x and z . The rate at which carriers recombine as a function of depth and distance away from the edge of the thin collecting junction is $e^{-r/L}$ where $r = \sqrt{x^2 + z^2}$. Since the focused MeV ion beam suffers from little lateral scattering, these calculations take no account of the generation volume of the ion induced charge carriers, as for the one-dimensional analysis [16]. These calculated results are based solely on charge diffusion since the drift component (i.e. the motion of carriers under the influence of the electric field) within the thin collecting junction is assumed to be negligible in this case.

Fig. 2(a) shows the calculated results for the variation of the charge pulse height produced with 850 keV protons away from the edge of the collecting junction. Values of diffusion length between 2 and 10 μm are shown, typical of those found in integrated circuits. The vertical scale in Fig. 2 gives the resultant charge pulse height in eV, assuming an average energy of 3.6 eV is required to create each electron-hole pair in silicon [18]. Thus for 850 keV ions, a

measured pulse height of 425 keV means that half the incident ion energy is measured as an IBIC pulse height of ~ 19 fC. If the noise level below which pulses are not detected in Fig. 2(a) is assumed to be 30 keV (the minimum level encountered in practice), then for $L = 10$ μm , pulses are detected up to 11 μm away from the junction edge, whereas for $L = 2$ μm , pulses are detected only ~ 1 μm away. From this, it can be seen that the ability to resolve two adjacent junctions in IBIC images is much poorer for a long diffusion length because of this slow decrease in pulse height away from a junction.

The effects of damage produced by the ion beam are incorporated into the model by assuming that the same types of defects with similar trapping cross-sections are created along the ion trajectory, with the total number of defects produced by each incident ion given by TRIM [19]. Fig. 2(b) shows the calculated change in charge pulse height away from the edge of the collecting junction for cumulative doses from zero to two thousand 850 keV protons/ μm^2 . The distance away from the junction edge at which pulses are detected decreases with cumulative dose because of the reduction in diffusion length. The rate of decrease of the charge pulses becomes progressively slower with increasing dose because the reduction of the diffusion length also becomes slower with increasing dose [16].

Heavier ions give similar behaviour as in Fig. 2 but with larger charge pulses because of their higher dE/dz , and faster rates of damage because of their higher rate of defect production. This means that charge carriers are detected further away from the junction edge at the start of irradiation but the image contrast alters more rapidly with increasing dose.

4. Measured IBIC results from a TA670 device.

Fig. 3 shows four IBIC images of a $40 \times 40 \mu\text{m}^2$ area of a TA670 device [20], produced using a beam of 14 MeV carbon ions focused to a 1 μm spot using the Sandia nuclear microprobe. The collecting junction extends 5 μm horizontally and 12 μm vertically, as outlined in white in Fig 3. Dark regions correspond to large measured pulses at the collecting junction and the grey regions correspond to smaller pulses and show the effects of charge diffusing laterally to the collecting junction. This region of the device has 7.3 μm of surface layers, and the structure is described in more detail in [20].

Fig. 4 shows a 3 μm wide vertical slice extracted from the middle of each of the four IBIC images in Fig. 3. These show the average charge pulse height as a function of distance along the 40 μm long vertical scan, for the four beam doses used in Fig. 3. Using this scale, a 14 MeV carbon ion would give a charge pulse height of 622 fC for complete charge collection at channel

245 on the vertical scale. On the first curve, for a dose up to $125 \text{ ions}/\mu\text{m}^2$, the maximum charge pulse height at the collecting junction is at channel 126 (equivalent to 7.2 MeV, and a collected charge of 322 fC). The amplifier lower threshold at channel 11 (equivalent to 570 keV) has been set just above the noise level, and pulse sizes below this are not recorded. Since proton induced charge pulses would be approximately twenty times smaller than those for 14 MeV carbon ions, they would not be detected above this high noise level, showing how heavier ions are able to produce IBIC images in cases where protons cannot. The junction is $12 \mu\text{m}$ long in the vertical direction, so it can be seen from Fig. 4 that the measured average charge pulse decreases quite slowly away from the junction centre, and then much more rapidly away from the junction edges.

The pulse height decrease is large from 125 to $250 \text{ ions}/\mu\text{m}^2$ and the decrease becomes progressively smaller for further increases in dose, as in the calculated curves in Fig. 2(b). After a dose of $500 \text{ ions}/\mu\text{m}^2$, the maximum charge pulse height measured at the junction has decreased by approximately 20% from its value at $125 \text{ ions}/\mu\text{m}^2$. The junction width also reduces with cumulative dose, again as in the calculated curves in Fig. 2. The full-width-at-half-maximum for the $125 \text{ ions}/\mu\text{m}^2$ curve is $19 \mu\text{m}$, whereas it has decreased to $16 \mu\text{m}$, for the $500 \text{ ions}/\mu\text{m}^2$ curve, a reduction of 15%. Calculated values for the charge pulse height decrease and decrease in junction full-width-at-half-maximum at $500 \text{ ions}/\mu\text{m}^2$ for this structure using the procedure described in section 3 are 25% and 19% respectively for 14 MeV carbon ions. There is thus a reasonable understanding and agreement on the mechanism underlying the changing feature sizes observed in IBIC due to ion induced damage.

5. Conclusions

The dose-dependence and lateral resolution of IBIC measurements is an important issue for its use in the verification of charge transport simulations of integrated circuits and the prediction of upset susceptibility. In this work the effects of lateral charge diffusion have been characterised using a model which calculates the amount of charge which diffuses laterally to a collecting junction as a function of diffusion length and ion induced damage. The calculated results have been shown to explain the dose-dependence of IBIC measurements from TA670 integrated circuits using 14 MeV carbon ions.

References

- [1]. M. B. H. Breese, G. W. Grime and F. Watt, *J. Appl. Phys.*, **72**(6) (1992) 2097
- [2]. K. M. Horn, B. L. Doyle, F. W. Sexton, J. S. Laird, A. Saint, M. Cholewa and G. J. F. Legge, *Nucl. Instrum. and Meth.* **B77** (1993) 355
- [3]. M. B. H. Breese, J. S. Laird, G. R. Moloney, A. Saint and D. N. Jamieson, *Appl. Phys. Lett.* **64**(15) (1994) 1962
- [4]. M. B. H. Breese, A. Saint, F. W. Sexton, H. Schöne, K. M. Horn, B. L. Doyle, J. S. Laird and G. J. F. Legge, *J. Appl. Phys.* **77**(8) (1995) 3734
- [5]. K. M. Horn, B. L. Doyle, D. S. Walsh and F. W. Sexton, *Scanning Microscopy* **5** (1992) 969
- [6]. F. W. Sexton, K. M. Horn, B. L. Doyle, J. S. Laird, M. Cholewa, A. Saint and G. J. F. Legge, *Nucl. Instrum. and Meth.* **B79** (1993) 436
- [7]. M. B. H. Breese, P. J. C. King, G. W. Grime and P. R. Wilshaw, *Appl. Phys. Lett.* **62** (1993) 3309
- [8]. H. Schöne, M. B. H. Breese, B. L. Doyle, *submitted to Nucl. Instrum. and Meth. B* (1997)
- [9]. C. Manfredotti, *these proceedings*
- [10]. L. Witham, D. N. Jamieson, *these proceedings*
- [11]. M. B. H. Breese, D. N. Jamieson and P. J. C. King, *Materials Analysis Using a Nuclear Microprobe*, Wiley, New York (1996)
- [12]. V. A. J. van Lint, T. M. Flanagan, R. E. Leadon, J. A. Naber and V. C. Rogers, *Mechanisms of Radiation Effects in Electronic Materials*, Wiley, New York, (1980)
- [13]. H. J. Leamy, *J. Appl. Phys.* **53** (1982) R51
- [14]. *Proc. 4th International Workshop on Beam Injection Assessment of Defects in Semiconductors*, Editors J. Piqueras, P. Fernandez and B. Mendez, *Mat. Sci. Eng* **42** (1996)
- [15]. C. Donolato, *Appl. Phys. Lett.* **34** (1979) 80
- [16]. M. B. H. Breese, *J. Appl. Phys.* **74**(6) (1993) 3789
- [17]. C. Donolato and R. Nipoti, *to be published in J. Appl. Phys.* (1997)
- [18]. C. A. Klein *J. Appl. Phys.* **39** (1968) 2029
- [19]. J. P. Biersack and L. Haggmark, *Nucl. Instrum. and Meth.* **174** (1980) 257
- [20]. K. M. Horn, M. B. H. Breese, B. L. Doyle *to be published in Nucl. Instrum. and Meth.*

Figure Captions

Figure 1. Schematic showing the geometry used to calculate two-dimensional charge diffusion effects. A thin depletion layer acts as the collecting junction, and no surface layers are assumed. The lateral distance away from the junction edge is x , and the depth at which carriers are generated is z .

Figure 2. (a) Calculated decrease in charge pulse height away from a collecting junction edge for 850 keV protons. The diffusion length is indicated by each curve. (b) Calculated decrease in charge pulse height away from the collecting junction edge for increasing irradiation doses of 850 keV protons, and an initial diffusion length of $5\text{ }\mu\text{m}$. The proton dose is indicated by each curve. An arbitrary level of 30 keV has been chosen in both graphs to represent the noise level, below which pulses are not detected.

Figure 3. TA670 IBIC images of a $40\times 40\text{ }\mu\text{m}^2$ area, produced using 14 MeV carbon ions. The cumulative doses/ μm^2 are: (a) 125, (b) 250, (c) 375, (d) 500. Fig. 4(c),(d) were recorded at slightly different vertical alignment to fig. 4(a),(b) so they have been displaced upwards by an appropriate amount. Each image has its own independent grey colour scale.

Figure 4. Vertical slices extracted from each of the IBIC images in fig. 4, from a central $3\text{ }\mu\text{m}$ wide region. The top curve with the squares is for the $125\text{ ions}/\mu\text{m}^2$ dose and the lowest curve with the inverted diamonds is for the $500\text{ ions}/\mu\text{m}^2$ dose.

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