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Electron beam dissipation volume effects on lateral and depth probing of semiconducting layers

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ABSTRACT: Monte Carlo (MC) simulations of electron trajectories for multi-layered sample geometries are used for studying the depth and lateral resolution under various experimental conditions. The resulting three-dimensional beam energy dissipation data is used to evaluate depth and radial beam exposure information, which provides an insight into depth and lateral resolution of electron beam techniques. The application of such simulations to compound materials and the various methods used for calculating average parameter values are discussed. Different average value calculation methods can result in significantly different electron doses, the choice of which can not be made a priori without comparison to experimental data.

1. INTRODUCTION

The evaluation of the beam effects across specific material boundaries can be carried using Monte Carlo (MC) simulations of electron trajectories, in which a multi-layered sample geometry is considered. From the three-dimensional energy dissipation information it is possible to evaluate accurate depth, lateral and radial energy doses that reflect in a simple analytical form the beam interaction. These can be used for understanding signals obtained in the various modes of scanning electron microscopy and for a study of the resolution of these modes, which can then be linked with experimental data.

Brouri et al. (1999) used EBIC in a STEM to study electrical activity in the junction region of Si diodes in cross section mode. An electron beam (diameter 3 nm, voltage 200 kVolts) was used to scan normal to the pn junction plane of devices thinned down (to electron transparency) in a wedge shape. The lateral resolution attained in EBIC linescans at room temperature was about 15 nm. Samples investigated at low temperature (105 K) showed a broadening in the EBIC linescan that varied with the sample thickness, which was not observed at room temperature, with a lower resolution of 6 nm. Hwang et al. (1994) used beam voltages of 200 kVolts in a converted TEM to study passivated devices. Although the electron beam range increases with accelerating voltage, the area of the beam dissipation volume intersection with the horizontal pn junction decreases. This results in a higher resolution, up to a claimed value of 50 nm for a junction 0.1 μm deep below a 0.2 μm nitride layer.

Experimental resolution depends not only on the beam interaction as part of the experimental conditions, but also on a combination of physical processes (e.g. carrier diffusion and drift) and practical considerations (e.g. contamination, mechanical vibrations, electrical noise, astigmatism). Optimisation of practical aspects, and careful selection of sample geometry allowed Norman (2000) to obtain a resolution of 20 nm in the CL mode at an optimal beam voltage of 1.5 kVolts. For lower beam voltages the resolution decreases due to instrumental considerations, while for higher voltages it decreases due to an increase in the energy dissipation volume.

The calculations involved in MC simulations consider the medium through which the electron is travelling as locally isotropic, with only one type of atoms interacting with the beam electrons. Compound materials, such as modern semiconductors, need a new simulation approach for describing averaged physical properties of the compound such as atomic number and mass. It is fairly accepted to

take the fractional weights weighted atomic masses of the constituents as the average atomic mass for the compound. For the atomic number, however, perhaps the most important parameter in MC simulations, there are various approaches, which can result in significantly different averaged atomic numbers. In the next section we will present some of these approaches, and compare them.

2. SIMULATION RESULTS

Wong and Elliot (1997) and Berger and Niedrig (1999) provide a summary with references to some of the methods used for calculating average atomic number and mass for compounds. For comparison purposes these methods have been implemented in the MC simulation used for this work, allowing easily changing the parameters of the specimen layers involved.

To analyse the effects of the various calculation methods a device corresponding to a heterojunction bipolar transistor (HBT), with layers of InP and InGaAs was selected. Table 1 shows the range of Z values calculated using the formulas from the above references. For the InGaAs, with a relative small Z range, an average value of Z = 40 was selected. For InP, with a larger range, the two extreme values were used in parallel simulations to see if such changes in Z could be seen in the results. The layer ordering and thicknesses for the device are presented in the inset in Fig. 2 a).

Compound	Max Z	Min Z	Avg A
InGaAs	41.3	38.5	91.2
InP	46.4	32.0	97.1

Table 1 – Calculated average Z and A values

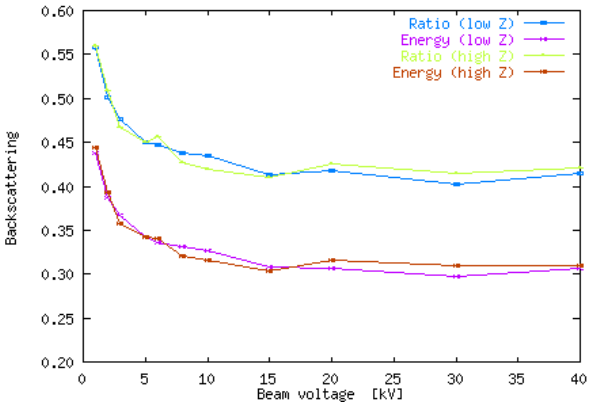
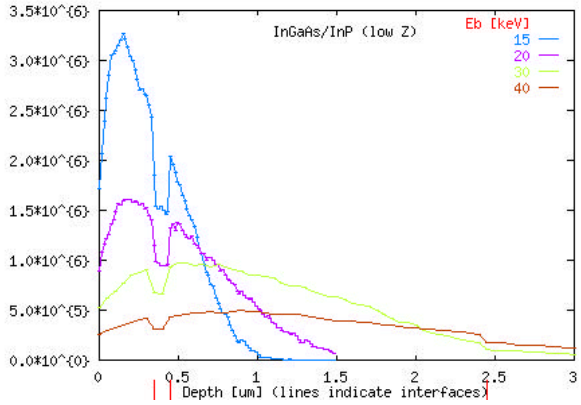


Fig 1. Backscattering coefficient (ratio) and energy for the test structures with the 2 different values of average atomic number for the InP layers

Fig. 1 shows the MC calculated backscattering (BS) coefficient and total energy values as function of beam voltage, for both test structures corresponding to the range values of the InP averaged atomic number. Up to 15 kVolts beam voltage there is no significant difference between the results for the devices. For higher voltages, the BS values for the high Z_{avg} InP layers are slightly higher, as expected from the BS variation with Z for single components.



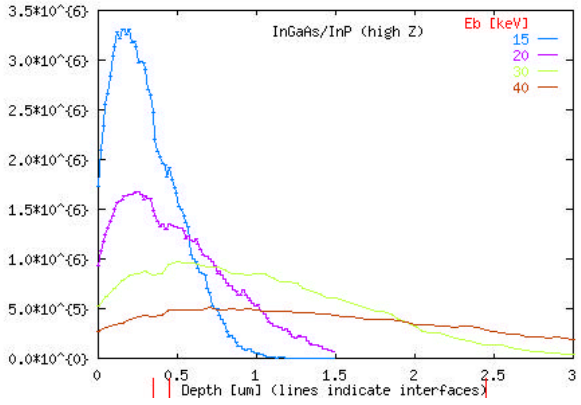


Fig 2 a) Depth dose curves at different beam voltages for the device with the low Z value for InP (the inset shows the structure of the device); b) corresponding results for the high Z value for InP

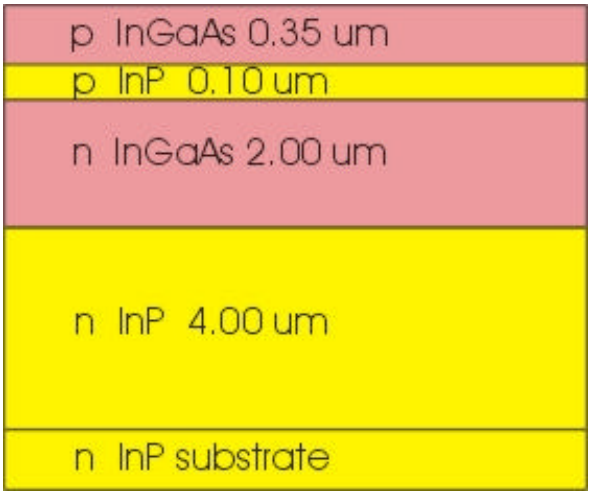
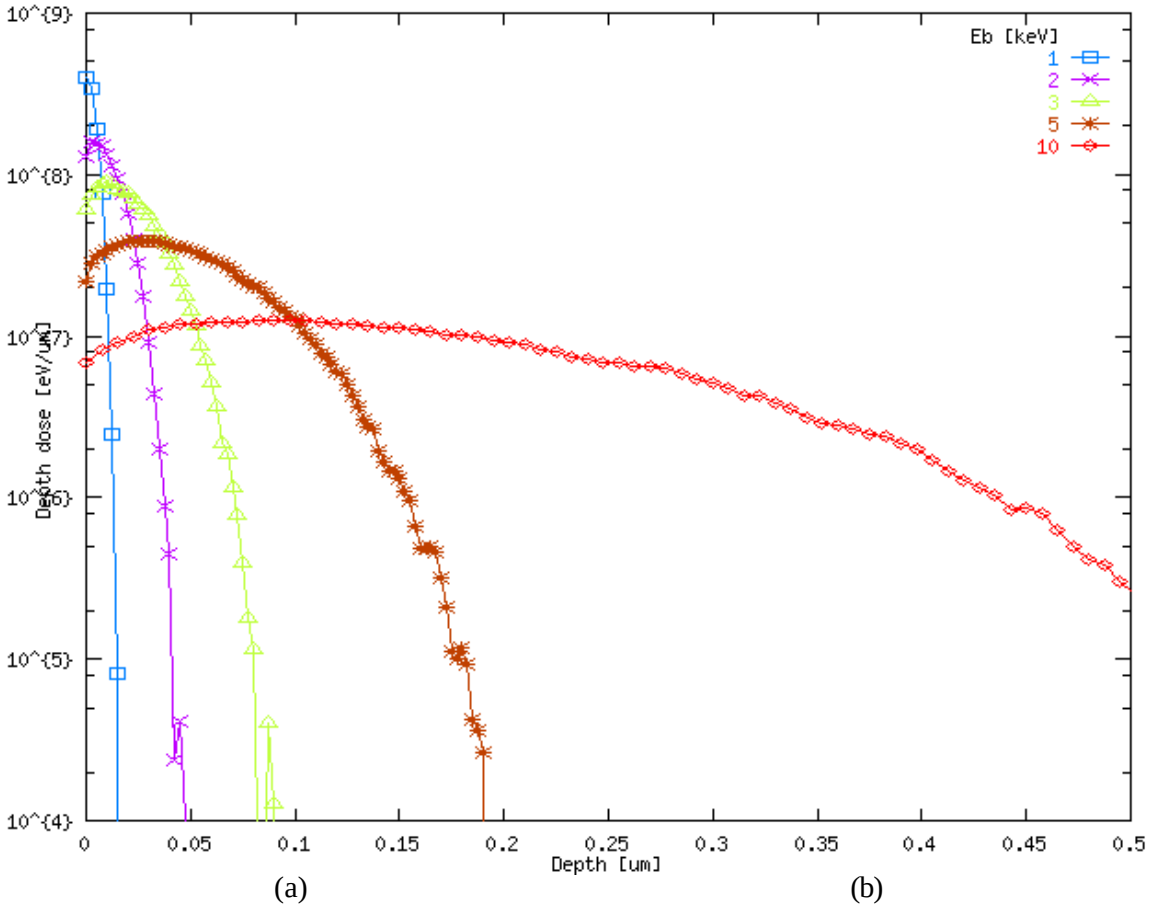


Fig 2 Inset: shows the structure of the device

Fig. 2 a) and b) present the depth doses calculated for the 2 structures, for a range of beam voltages. Below the x-axis of each graph some of the layer boundaries have been indicated, at 0.35, 0.45 and 2.45 µm. The overall depth dose function is similar for both devices in the regions corresponding to the InGaAs layers. For the InP layer at 0.35 µm depth there is a marked reduction in the value of the depth dose for the low Z InP. This effect shows itself with greater significance the lower the beam accelerating voltage used, and less intensely for the second InP layer at 2.45 µm depth.

Fig. 3 presents MC simulation results for a bulk GaAs specimen for normal beam incidence. In Fig. 3 a) the depth dose is plotted with a log y-axis to highlight the maximum beam depth of penetration in the specimen. This depth, indicated by the almost vertical section of the curves, is likely to be the depth resolution attainable for signals that depend on the beam interaction volume. Thus, for a beam voltage of 2 kVolts the graph indicates a maximum penetration

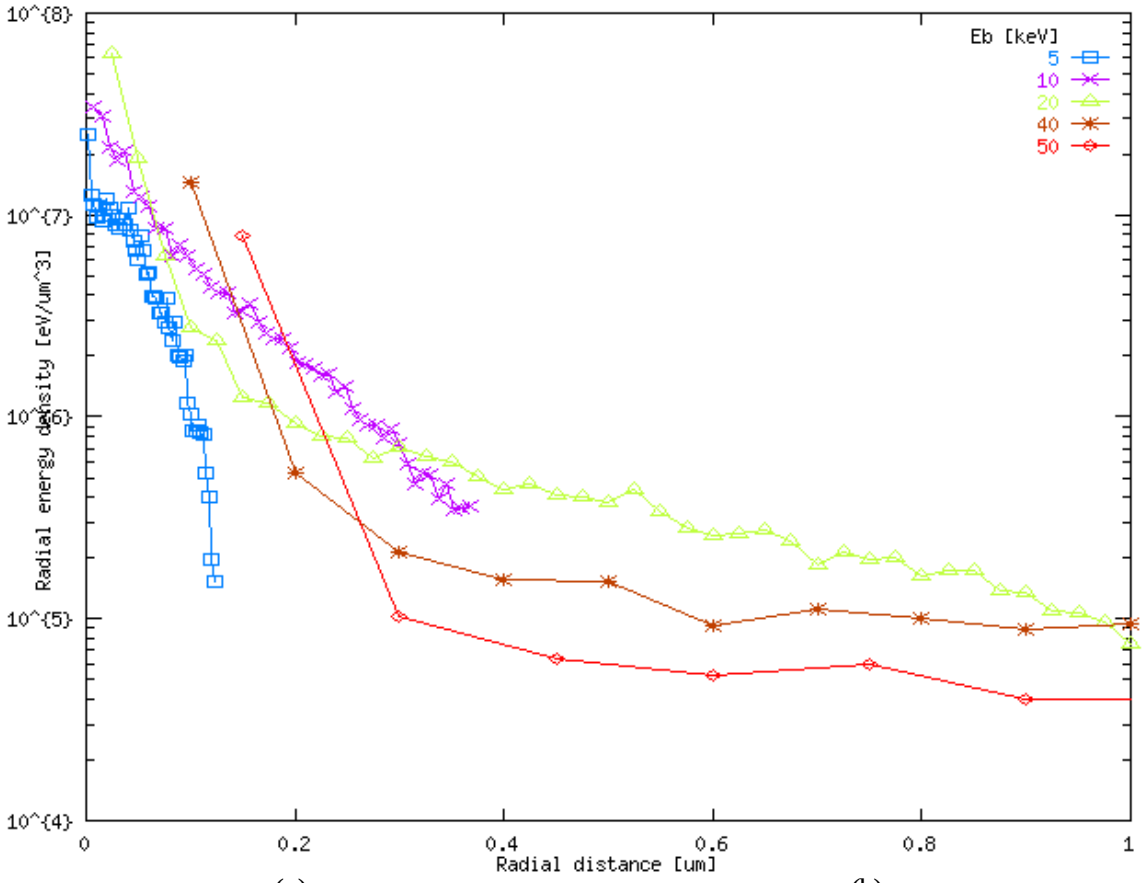


(a) (b)

Fig 3(a) Electron depth dose density curves at different beam voltages for a GaAs bulk device for different beam accelerating voltages

depth of about 50 nm, and for a beam voltage of 5 kVolts this becomes 0.2 µm. These simulations used the same number of electrons for each case, and therefore the total energy deposited is

proportional to the beam accelerating voltage. The depth dose curves presented have been plotted for the same total beam energy, by dividing the dose value by the beam accelerating voltage.



(a) (b)

Fig 3(a) Electron radial energy density curves at different beam voltages for a GaAs bulk device for different beam accelerating voltages

The radial beam energy distribution as a function of depth in the sample is important for the determination of the experimental lateral resolution attainable. One way of presenting this information is as equal energy profiles, as done in MC simulation studies of electron resist exposure, where profiles for a specific energy density are matched with the shapes developed after the resist exposure.

An alternative to the equal density profiles is to graph the energy deposited at a particular depth as function of the distance from the beam incidence point. Fig. 3 b) presents results of the calculation of the radial energy density for various beam-accelerating voltages, at a selected depth of 0.1um in the GaAs layer. From Fig. 3 a) it is clear that only beam voltages higher than 3 kVolts will penetrate to such a depth. The calculation of the radial energy density was carried out by averaging radially the energy deposited at the selected depth, as a function of the "energy deposition element" distance from the beam incidence point (assuming complete planar symmetry). In these plots the actual total deposited beam energy was used, and therefore the results are comparable for same beam current experiments.

The lateral resolution, at a depth of 0.1 μm in bulk GaAs, can be estimated from Fig. 3 b): for a beam voltage of 5 kVolts the maximum radial dissipation occurs at about 0.15 μm, while for the other conditions the dissipation profile extends further than 1.0 μm in the lateral direction. It is interesting to note that the actual energy density at distances greater than about 0.2 μm is larger for lower beam voltages. This can be understood in view of the fact that the actual dissipation volume is proportional to the beam accelerating voltage, and more of the energy at higher voltages will get deposited deeper in the specimen.

3. DISCUSSION

The 'correct' method for calculating averaged atomic and mass values to be used in the MC simulation of compounds depends on the quantity or type of signal that is ultimately evaluated from the results. Donovan and Westphal (2000) point out that as electron-solid interactions are not affected by mass, a realistic model for calculating averaged Z should be based on atomic or electron fractions of the constituents. They find this particularly suitable for averaging electron backscatter coefficient data and x-ray continuum intensities.

Berger and Niedrig (1999) find that a good fit between the experimentally measured and the MC calculated angular distribution and coefficient of electrons backscattered from a W-Cu compound is obtained using Buchner's (see their reference) relation of a quadratic weighed average of the atomic numbers ($a_i Z_i^2$). The large gap in atomic numbers between the Cu and W (29 and 74, respectively) and the use of tilting conditions for the experiment are conditions that enhance the meaningfulness of the result.

The depth doses calculated for the HBT devices presented here show a marked difference depending on the value selected for the InP atomic number. EBIC and CL experiments depend on the carrier distribution within the device layers, and therefore are sensitive to variations in the electron depth dose function. The selection of which averaging method is preferable can only be done when corresponding experimental data is compared with the MC simulation values.

A three-dimensional energy dissipation volume results from the beam interaction with the specimen. When this volume has some form of symmetry it is possible to condense this information to more usable forms, such as an energy depth dose and a radial energy dissipation density. The present MC simulation calculates this volume, and allows the evaluation of corresponding electron doses. The information from these dose functions allows the evaluation of beam interaction dimensions, which are linked to the possible experimental resolution. The results presented for the GaAs sample show how these can be used to better understand the resolution issues and their dependence on beam accelerating voltage conditions.

4. CONCLUSIONS

MC simulations are a powerful tool for the study of electron beam interaction with semiconducting devices. Specific aspects of the simulation process, such as which method to use for deriving Z values for compounds, need to be selected after matching calculated and experimental data. This paper has shown that for compounds in which the constituents have large atomic number differences the selection of a representative average atomic number needs to be made based on fits of the simulation to relevant experimental data. It is not possible to use previous good fits of unrelated experimental results in order to decide which is the best method to average atomic number of compounds.

The reported enhanced experimental resolution work with semiconducting devices, either using higher electron beam energies (200 kVolts), or lower electron beam energies (about 1 kVolts), can be simulated and understood by performing MC simulations for these experimental conditions. These simulations can also be used to select experimental conditions in which the actual probing conditions and resulting beam energy dissipation are known in advance.

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