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EXTRAPOLATED RANGE FOR LOW ENERGY ELECTRONS (< 1 keV)*

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Abstract

The Secondary Electron Emission (SEE) process plays an important role in the performance of various devices. For instance, the multipactor mechanism, driven by SEE, affects radio-frequency components of space missions. SEE is also a concern in other domains, for instance the accelerator physics community, where the beam lines stability can strongly be affected by the initiation of electron clouds. Electron extrapolated range, which is a measure of the penetration distance of electrons in solids is a fundamental parameter required to understand and model this SEE mechanism. Our goal, by means of simulations, is to provide a better knowledge of the range of electrons at low energy (<~10 keV), the domain of energy where the risk of triggering an electron cloud is maximum. We have developed a Monte Carlo electron transport code for low energy electrons [~eV, ~10 keV]. It has been used to study the practical range of electrons in the energy domain of interest for the SEE machanism. This work proposes to formulate, below ~10 keV, an analytic range vs. energy expression.

INTRODUCTION

As mentioned in the abstract, the extrapolated range of electrons, which is a measure of the penetration depth of electrons in solid materials, is of great interest in many different domains that operate or are subject to electron beams [1-7]. For instance, the relevance of surface analysis methods, such as electron spectroscopy [1] depends closely on the accurate knowledge of the characteristics of the electrons emitted by the scanned surfaces. Secondary electrons are also used to magnify the contrast of images in scanning electron microscopy. In that scope, the escape depth of electrons is of common use. The need of an accurate knowledge of the range of low energy electrons emitted from a surface can thus be easily understood. The discussed Secondary-Electron-Emission (SEE) property is known to play also an important role in the performance of various devices [2, 3]. Depending on the application, the materials shall be rigorously selected in order to enhance or lower the secondary-electron emission. For example, the multipactor effect in microwave and millimeter wave power tubes of satellites is sometimes mitigated by covering the walls of the devices with materials presenting low secondary electron emission level [4].

The capability of electrons to escape from a surface is closely related to its energy and thus the distance it can travel in a given material, i.e. its range. In that scope, the electron "extrapolated" range is commonly used [5, 6]. This notion of "extrapolated" range will be returned to later in the paper. For now the range and the "extrapolated" range will not be distinguished. They are useful parameters for determining escape depth, secondary electron emission yield, or deposited dose in materials… all these parameters being related to each other's. Empirical formulas connecting the range to the energy of the incident electrons can be found in the literature [5, 6, 8-10]. But, due to experimental difficulties, most of formulas proposed in the past, which have been deduced from experimental transmission measurements, fail below 1 keV incident energy, to estimate properly the right electron penetration distances. These formulas which are at the basis of many secondary electron emission models, are clearly not suited for such use, limiting the relevance of SEE models. Indeed, most of time the secondary electron emission becomes critical when its level overpass 100 %, precisely below ~1 keV for most materials. These are precisely, the electrons belonging to that domain of energy, that initiate electron clouds that form in accelerator beam lines [7]. We have developed a Monte Carlo electron transport code for low energy electrons [~eV, ~10 keV], that is proposed to be part of the June 2021 release of GEANT4 [11-13]. This low energy module of GEANT4 has been used to study the practical range of low energy electrons (<10 keV) in order to formulate, in that energy domain and down to ~10 eV, an analytic range vs. energy expression for incident electrons. This has been used to extend the validity domain of the range/energy formula proposed by Weber [8-10] which now can be applied down to few eV.

TRANSMISSION RATE AND "EXTRAPOLATED" RANGE OF ELECTRONS

The distance that can be travelled in a solid by an electron of a given energy E must be differentiated from its penetration depth. Electrons are highly scattered by coulombian interactions with nuclei, and present very disordered trajectories. Consequently the total distance that can be travelled by an electron in a solid (range or theoretical range) can be very different from the penetration depth (extrapolated or practical range), (Fig. 1). Each individual electron has its own trajectory that differs from the others, in term of direction, total distance travelled and penetration depth. For these highly scattered particles, a method is commonly employed to define an average penetration depth. It is summarized in Fig. 1. The average penetration depth can be extracted from the transmission probability. The transmission rate can be known experimentally or numerically thanks to Monte Carlo calculations (Fig. 1).

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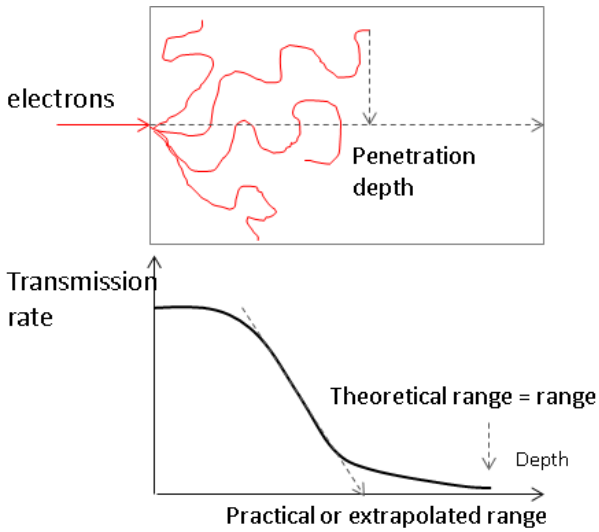

Figure 1: Electrons trajectories with the definition of the range and the practical range.

The intersection with the X-axis of the tangent of the transmission rate curve, taken at its steepest point provides what is defined as the "practical" or "extrapolated" range. This parameter provides a more representative value of the average penetration distance of electrons into the matter, than the total range that represents the sum of all elementary paths along the trajectory of an electron. The theoretical range can be easily deduced from the electronic stopping power of the electrons (dE/dx), but it can be very different up to twice the value of the practical range. This is the reason why the practical range is often preferred to the theoretical range to characterize the behaviour of electrons into the matter. In addition, it can be used very simply to estimate the deposited dose in a target material or in analytical secondary electron emission yield model [5, 6]. Some more details will be found in a publication submitted to Applied Surface Science journal [14].

Several authors proposed analytical expressions to express the dependency of the practical range r to the incident energy E of the electrons (r(E)). We have chosen to upgrade at low energy, the expression provided in ref. [8, 10]. This formula has the advantage to be derivable as a function of the energy, which facilitates its use for developing analytical dose or SEY expressions. But like all the others expressions that can be found in the literature, this formula, deduced from experimental data, is valid only above ~1 keV. Below this energy, the incident electrons reach the energy level of the internal electronic shells of the atoms, that makes any extrapolation of this formula below ~1 keV very hazardous. In addition, due to experimental issues, it is very difficult to perform accurate transmission rate measurements below 1 keV. At this energy level the range of electrons are in the order of several hundred of nanometers. Any measurements would require handling thin samples of several tens of nanometers. Consequently, below 1 keV the use of Monte Carlo simulations is necessary to estimate the penetration distances of low energy electrons into the matter.

MONTE CARLO ELECTRON TRANSPORT CODE

But, the transport of electrons below ~1 keV is not so straight forward. For the same reasons as the one given to explain the experimental difficulties in measuring the transmission rates at low energy, it is difficult to perform Monte Carlo simulations of electrons below ~1 keV. The incident electron energy reaches the energy level of the atomic shells. In addition the population of weakly bound electrons presents collective excitations (plasmon) having specific energy levels that must be taken into account. Specific Monte Carlo simulations are thus required to perform transport of low energy electrons. We have worked for some years now on the development of such a code [11-13]. The latest developments of the MicroElec module [13] are yet to be released in the june 2021 version of GEANT4 [15]. The calculation of the inelastic interaction cross section is based on the dielectric function theory, and the elastic interaction cross section with nuclei is deduced from a partial wave treatment of the Schrödinger equation [16]. All details can be found in the following references [11-13].

The transmission rates of electrons having energies between 10 eV and 5 keV have been estimated for 11 different elements (C, Be, Al, Si, Ti, Ni, Fe, Cu, Ge, Ag, W). The transport of the electrons is performed in a semi-infinite slab. 10000 incident electrons, impinging the volume with normal incidence, are simulated for each material, and for each energy. The extrapolated ranges have been deduced for all these materials according to the method described in the previous section (Fig. 1).

PRACTICAL RANGE DOWN TO ~10 eV

The practical range has been calculated for 11 different materials with the low energy MicroElec module of GEANT4 (Fig. 2). As can be seen on this figure, below 1 keV the practical range is curved and reaches a kind of plateau which levels depends on the nature of the material. This behaviour strongly deviates from the shape estimated by the Weber formula [8]. The formula defined for high energy (>keV) is clearly unsuitable at lower energies. Above some keV the practical ranges normalised to the density of the different materials (expressed in g/cm²) converge to each other's. At high energy, the distance that can be travelled in a solid by an electron depends mainly of the electronic density of the medium. Below ~1 keV this is no more the case, because of the specificity of the band structures of each materials, which play a more and more important role as the energy diminishes. Below 14.5 keV, the GEANT4 data have been fitted by a new empirical formula (1), in order to take into account the bend of the curves. Above 14.5 keV the Weber formula is preserved.

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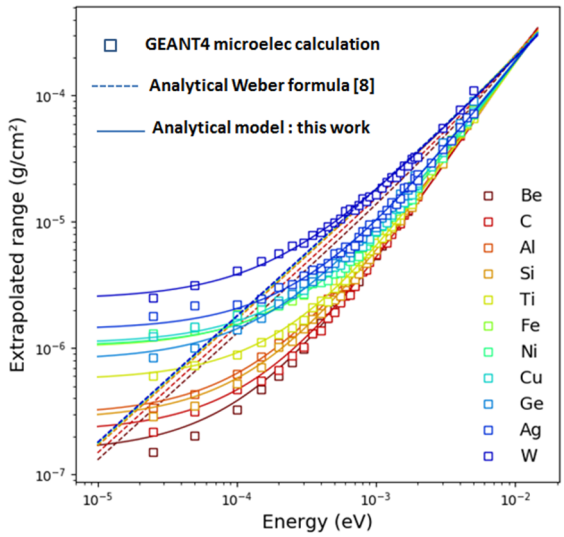

Figure 2: Practical range for 11 elements. Comparison is made between GEANT4 Monte Carlo simulation, our analytical expression and the formula given in [8].

$$r(E) = \begin{cases} D(E+E_r)^F : 10eV < E \leq 14.5keV \\ AE\left[1 - \frac{B}{(1+CE)}\right] : E \geq 14.5keV \end{cases} \quad (1)$$

$$R_{0,Al} = 4.07 \cdot 10^{-7}\ g/cm^2\ E_0 = 14.5\ keV$$
$$A = (1.06 \cdot Z^{-0.38} + 0.18) \cdot 10^{-3}\ g/cm^2\,.keV$$
$$B = 0.22 \cdot Z^{-0.055} + 0.78$$
$$C = (1.1 \cdot Z^{-0.29} + 0.21) \cdot 10^{-3}\ g/cm^2\,.keV$$
$$E_r = \frac{E_0}{\left(\frac{r(E_0)}{G \cdot R_{0,Al}} - 1\right)^{\frac{1}{F}}}, D = \frac{r(E_0)}{(E_0 + E_r)^F}$$

Table 1: Model Parameters

Z	G	F
4	0.51	1.64
6	0.74	1.65
13	1	1.55
14	0.92	1.58
22	1.91	1.59
26	3.46	1.48
28	3.58	1.52
29	3.72	1.47
32	2.71	1.38
47	4.78	1.4
74	8.2	1.12

The model has been parameterized for 11 different elements (Table 1). Extension to all elements is fully detailed in an extended article submitted to a journal [14].

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