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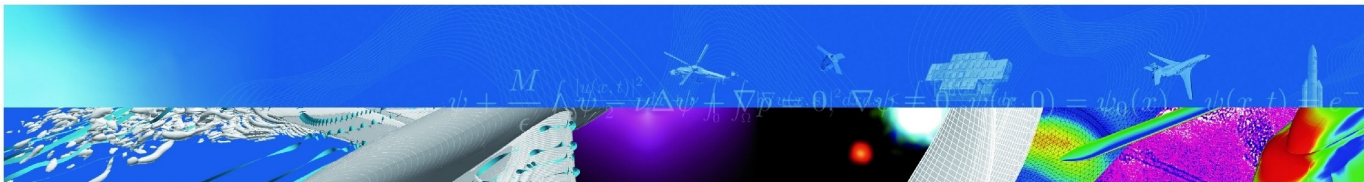
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COMMUNICATION A CONGRES

Extrapolated Range Expression for Electrons Down to ~10 eV

C. Inguibert, J. Pierron, M. Belhaj, J. Puech (CNES)

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Extrapolated range expression for electrons down to ~10 eV

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Abstract— —. The commonly used expressions of the “extrapolated range” of electrons are given for energies down to ~1 keV. An empirical equation valid down to ~10 eV has been formulated for 41 different elements.

Index terms— Space Environment, electron, range, practical range.

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Extrapolated range expression for electrons down to ~10 eV

C. Inguibert, J. Pierron, M. Belhaj, J. Puech

Abstract— The “extrapolated range” of electrons is a very practical physical parameter widely used in many applications. The commonly used analytical expressions are given classically for energies down to ~1 keV. An empirical equation for the extrapolated range of electrons in condensed matter has been formulated. It is given for 41 different elements and for energies ranging from ~10 eV up to some tens of MeV.

Index terms– Space Environment, electron, extrapolated range.

I. INTRODUCTION

The extrapolated range of electrons is a measure of the penetration distance of electrons in solid materials. Its knowledge is of great interest in many different domains that operate or are subject to electron beams. For instance the electron spectroscopy [1] is based on high-resolution measurements on the characteristics of emitted electrons that escape only from a depth of a few nanometers. Hence, this kind of surface analysis method requires the knowledge of the range of electrons, for energies down to few tens of eV. The discussed Secondary-Electron-Emission (SEE) process plays also an important role in the performance of various devices [2, 3]. Depending on the application, the materials are rigorously selected in order to enhance or lower the secondary-electron emission. In the field of space technologies, we can mention the case of multipactor phenomenon that may occur in Radio-Frequency (RF) components of satellites [4]. For example, in microwave and millimeter wave power tubes, low secondary-electron-emission materials are required in order to prevent the triggering of this multipactor effect. In this scope, the electron extrapolated range is a fundamental parameter commonly used in SEE yield models [5, 6].

In the past, many studies have led to the publication of several empirical formulas [7-16]. Most of them have been deduced from experimental transmission measurements. But, at low energy, below 1 keV, the existing experimental difficulties make the evaluation of the extrapolated range relationship quite difficult. Consequently, the validity domains of the analytical expressions that can be found in the literature [7-16] extend at best down to ~1keV. However some applications, such as secondary electron emission need models relevant down to some eV. In that work, we propose to use a Monte Carlo electron transport code (OSMOSEE [17, 18]) to determine numerically the extrapolated ranges of the electrons

down to few tens of eV. This has been used to extend the validity domain of the range/energy formula proposed by Weber [9, 11] which now ranges from few tens of eV up to several tens of MeV.

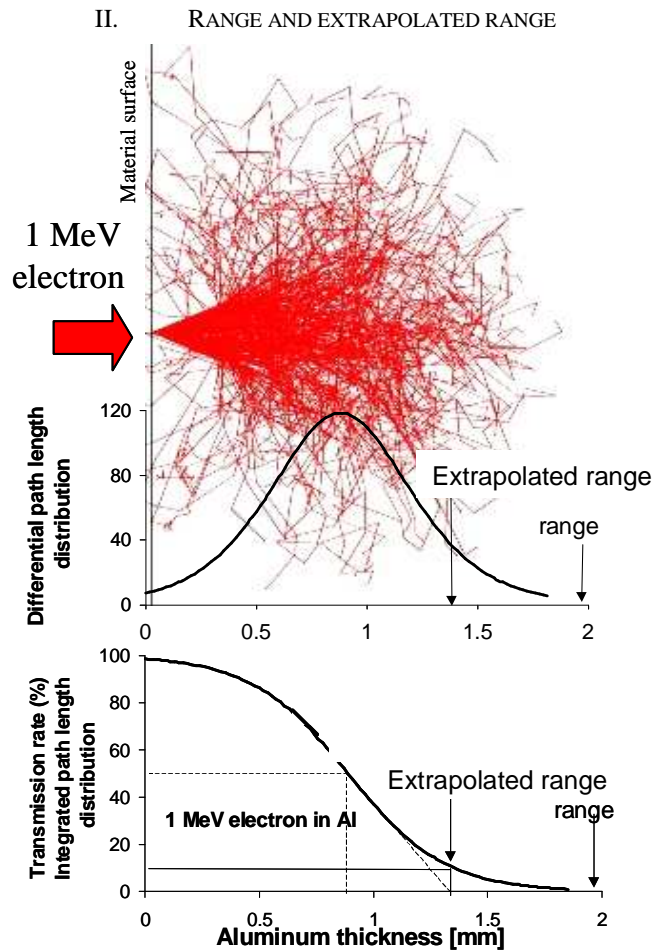


Fig. 1. Definition of the range and the extrapolated range of electrons.

In a target material, the incident electrons are slowed down by successive inelastic interactions with electrons of the target atoms. Subsequent to these interactions, each particle has an individual trajectory. The path length of this trajectory is the total distance traveled until the electron comes to rest. This distance remains absolutely unknown since the behavior of a particle beam follows statistical laws which only make it possible to define an average path length known as the "range" of the particles. At a given energy E , the range is defined as the average of path lengths of the electrons in a semi-infinite slab. It can be evaluated by the integral of the reciprocal of the stopping power (dQ/dx) over energy from a final to an initial value.

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$$range(E) = \int_0^E \frac{1}{dQ/dx} dQ \quad (1)$$

This value is called the Continuous-Slowing-Down Approximation (CSDA) range. But, for many applications, the projections of the paths of the particles in a given direction, representative of the studied geometry, can have a more practical importance. For electrons, that are highly scattered, two parameters are commonly used: the extrapolated range and the practical range. The extrapolated range is commonly defined as the point where the tangent at the steepest section of the transmission curve intersects with the thickness axis (X-axis) [15, 16] (fig.1). Analogously, the practical range can be defined by some authors, with the depth-dose curve in place of the transmission curve. According to these definitions the practical range and extrapolated range differ slightly, but they have often been used interchangeably. In the present work we will focus on the definition of the extrapolated range.

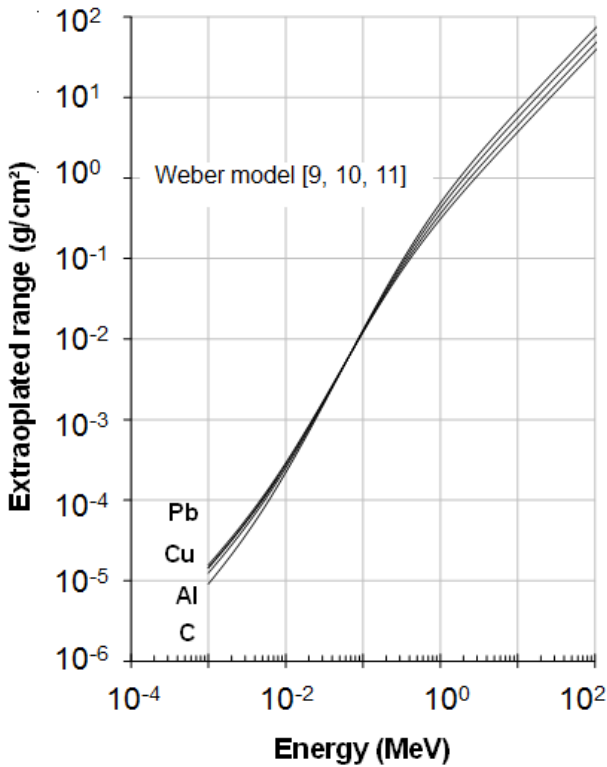


Fig. 2. Range vs. energy of electrons Weber formula (2) & (3).

A number of authors have proposed empirical range-energy expressions describing the electron extrapolated ranges in various materials [7-16]. The aluminum has been by far, the most extensively studied material. The range energy relationships are most of time of the form:

$$x = k \cdot E^n \quad (2)$$

Katz and Penfold [7] have drawn up a very thorough compilation of numerous experimental results for aluminum and have proposed an empirical formula for the extrapolated range of electrons with energy comprised between 10 keV and 3 MeV. In this expression, widely used in the past, the n factor

is dependent of the energy of the electrons (x in mg/cm^2 , $k = 412$, $n = 1.265 - 0.0954 \ln(E)$). Sometimes n is found to be dependent of the absorber [8]. Weber [9] proposed a different expression, valid for aluminum in the energy region [3 keV, 3MeV]. Kobetich and Katz [10, 11] extended this model to the 0.3 keV- 20 MeV range by adjusting the constants:

$$x = AE \left[1 - \frac{B}{(1+CE)} \right] \quad (3)$$

where x is the practical range, E the kinetic energy of the electrons, $A=5.37 \cdot 10^{-4} g/cm^2/keV$, $B=0.9815$ and $C=3.123 \cdot 10^{-3} keV^{-1}$ [10]. Kobetich [11] improved this formula making it dependent on the atomic number Z of the material:

$$\begin{aligned} A &= (1.06 \cdot Z^{-0.38} + 0.18) \times 10^{-03} g/cm^2.keV \\ B &= 0.22 \cdot Z^{-0.055} + 0.78 \\ C &= (1.1 \cdot Z^{-0.29} + 0.21) \times 10^{-03} / keV \end{aligned} \quad (4)$$

The practical range calculated with this model is presented in Fig. 2 for four different materials (Pb, Cu, Al & C). Some other models can be found in the literature [12-16]. Most of them suppose the practical range to tend to zero according to a power law, and contrary to the Weber expression, they are not relevant on the whole energy range. The Weber expression has also the advantage to be able to either express the extrapolated range x as a function of the energy E or inversely E as a function of x . This work proposes to improve this model (formula (2) & (3)) [9] in order to extend its validity down to ~ 10 eV.

III. LOW ENERGY MONTE CARLO TRANSPORT CODE

For that purpose, the Monte Carlo code OSMOSEE [17, 18] dedicated to the transport of low-energy electron into matter has been used. Incident electrons traveling in a solid with energies in the [eV, keV] range, are scattered inelastically in collisions with the electrons of the material. In that energy domain the scattering with the valence electrons is the dominant loss mechanism. An effective way to evaluate the interaction cross sections with these valence electrons, is based on the complex dielectric function theory [19, 20]. The version 2.3 of the OSMOSEE code [18] is based on that formalism and the use of the optical data of reference [21]. A detailed description of the code can be found in references [17] and [18]. The general methodology is briefly reminded here.

The inelastic interactions of incident electrons with electrons of the target atoms are modeled using the energy-loss function:

$$\Im m \left[\frac{-1}{\epsilon(\hbar\omega, q)} \right] \quad (5)$$

where $\hbar\omega$ and q are respectively the energy and momentum transfers of the electron, $\epsilon(\hbar\omega, q)$ is the complex dielectric function of the target material. The energy-loss function at $q=0$ is obtained from optical data [21], fitted by a set of Drude-functions, then extended to $q \neq 0$ using dispersion relations [19, 20]. The differential interaction cross section is given by the following expression:

$$\frac{d^2 \lambda^{-1}(E)}{d\hbar\omega \cdot dq} = \frac{1}{\pi\alpha_0 E} \Im m \left[\frac{-1}{\epsilon(\hbar\omega, q)} \right] \cdot \frac{1}{q} \quad (6)$$

The inelastic mean free paths are deduced by integration of equation (6) on $(\hbar\omega, q)$ domains defined by laws of energy and momentum conservation [20, 21].

Individual and collective interactions with electrons of the conduction band are treated. The interaction cross sections with the core electrons are also extracted according to this formalism. The coulombic elastic interactions with the atoms are modeled according to the interaction cross section, calculated with the ELSEPA code that performs the relativistic (Dirac) partial-wave calculations for scattering by a local central coulombic potential [22]. Up to now, only three different materials have been implemented in the OSMOSEE code: aluminum, silver and silicon. OSMOSEE2.3 code, allows the quantification of different quantities such as backscattered electron yield, secondary electron emission yield, transmission probabilities, range and extrapolated range of electrons. The transmission probabilities and the extrapolated ranges have been evaluated for the three different materials (Al, Ag, Si) (Fig. 3, Fig. 4 & Fig.5). These functions have been used in order to define and parameterize an energy/range analytical formula relevant down to ~ 10 eV.

IV. TRANSMISSION PROBABILITY

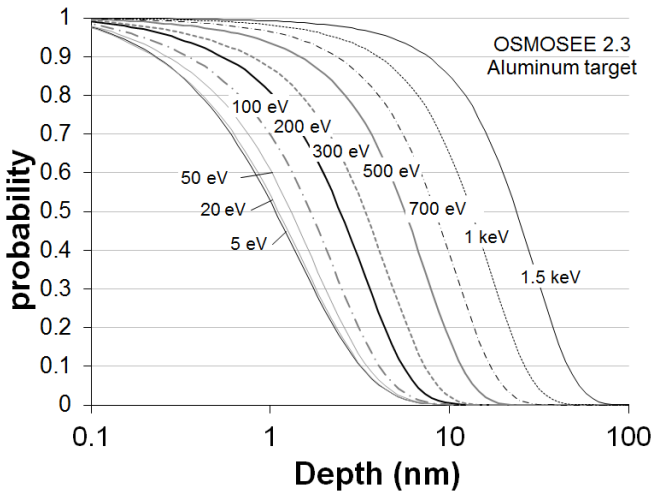


Fig. 3. Transmission probability of normally incident electrons on aluminum targets. The incident energies are in the range [5 eV, 1.5 keV]. The calculations have been performed with the Monte Carlo code OSMOSEE 2.3.

The extrapolated range is deduced from the transmission probability calculated with OSMOSEE2.3 Monte Carlo code according to the method describe in the section II (Fig. 1). The transmission functions have been evaluated for three different materials (Al, Si, Ag) as a function of the incident electron energy. They are presented in the figures 3 & 4 for aluminum and silver. The penetration depths are higher in aluminum than in silver which have a higher density. For 1.5 keV electrons the penetration depth can reach hundred of nanometers in

aluminum. It reaches only 20 nm in silver. On the contrary, at low energy around few eV the penetration depth in the two materials are comparable (\sim nm).

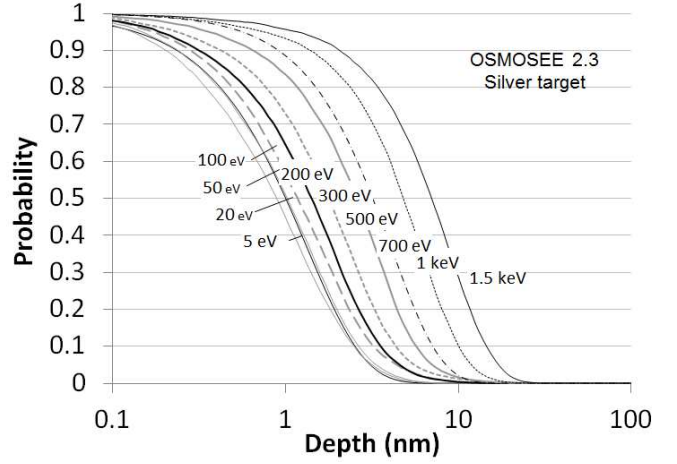


Fig. 4. Transmission probability of normally incident electrons on silver targets. The incident energies are in the range [5 eV, 1.5 keV]. The calculations have been performed with the Monte Carlo code OSMOSEE 2.3.

V. EXTRAPOLATED RANGE

A. Monte Carlo extrapolated range

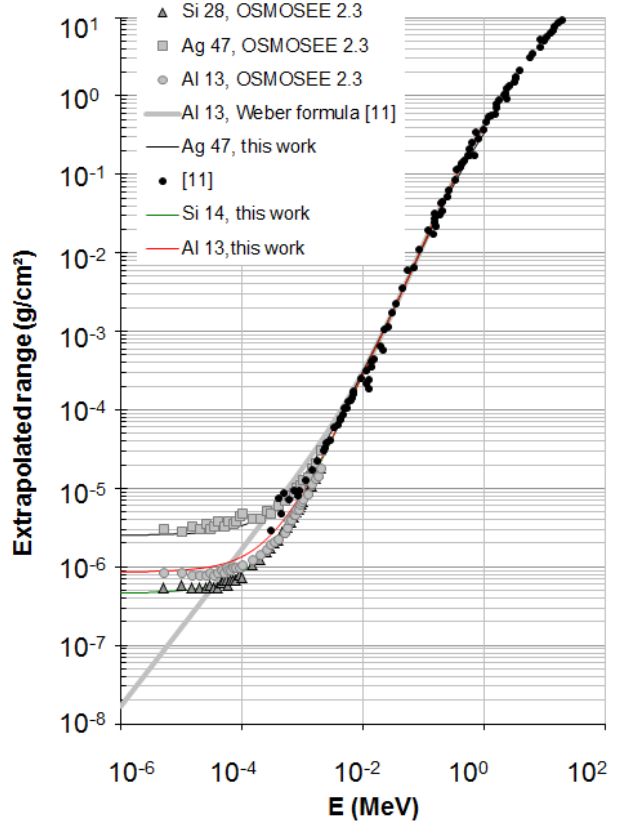


Fig. 5. Electrons range/energy function given by the formula (6) and compared to OSMOSEE 2.3 Monte Carlo calculations. Below some hundred of eV the Weber model (Grey curve) does not reproduce faithfully the Monte Carlo simulations.

For Si, Al, and Ag target materials, and according to the method described in Fig. 1, the extrapolated ranges of incident electrons, have been extracted from the transmission probabilities calculated with OSMOSEE2.3 (Fig. 3 & Fig. 4). The extrapolated ranges show a typical behaviour at low energy (Fig. 5). Below some hundred of eV, the extrapolated range reaches a kind of plateau region which level depends on the material (Fig. 5).

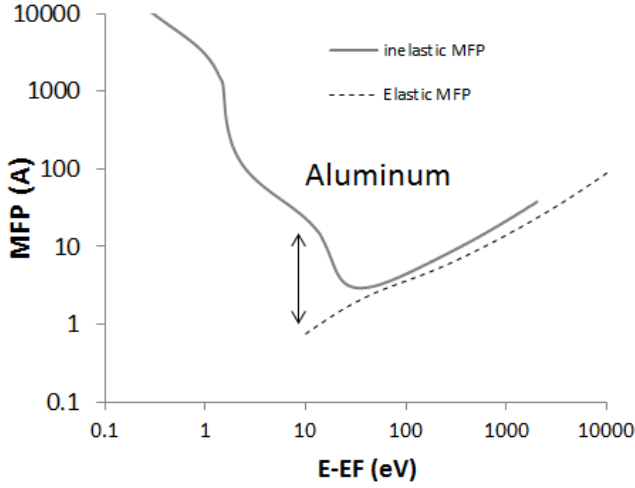


Fig. 6. Mean free path of electrons in aluminum target. The inelastic mean free path increases strongly below 50 eV. The elastic interaction becomes the dominant process.

At these energies, the transport of electron is driven by two kinds of interactions: The inelastic electron/electron interactions, that lead to important energy losses, and the elastic interactions with the nuclei, that deflect strongly the trajectory of the moving electrons without any energy loss. At very low energy ($< \sim 50$ eV), the elastic interactions with nuclei become more and more important. As can be seen on Fig. 6 for aluminum, around ~ 10 eV the elastic mean free path is an order of magnitude smaller than the inelastic mean free path. At these low energies, the electrons are strongly scattered by the nuclear interactions while conserving their energy. The transport of electrons can be assimilated to a random walk motion. The electrons are highly scattered without any energy loss, until an inelastic interaction occurs, leading the particle to come to rest. Hence, the electron is able to travel a relatively long distance before being stopped by an inelastic interaction. The extrapolated range of the electrons is no more proportional to the incident energy, and the range/energy function stabilizes (Fig. 5). A plateau region is observed on the practical range function at low energy. The level of this plateau region changes from a material to another (Fig. 5) as a function of the relative values of the inelastic and elastic mean free paths.

B. Analytical expression

Above some keV, the Weber formula is in good agreement with both the Monte Carlo simulations of OSMOSEE and the experimental data of ref. [11] (Fig. 5). But below ~ 1 keV the Weber formula (2) is no more applicable. As can be seen on Fig. 5, below 1 keV, the commonly used power law expressions [7, 8, 12-16] are not able to predict correctly the practical range of electrons. Consequently, the Weber's model [9, 11] has been extended to be relevant in the whole domain of energy.

In our new expression (6), the use of the model of Weber (2) [11] is maintained for energies greater than 14.5 keV. Below this energy, the formula (2) has been replaced down to ~ 10 eV, by a power law function (6) dependent of the absorber. As can be seen in Fig. 5, the analytical expression provides extrapolated ranges in very good agreement with the Monte Carlo simulations OSMOSEE2.3.

$$\begin{aligned} x &= D(E + E_r)^F & 10 \text{ eV} < E < E_0 = 14.5 \text{ keV} \\ x &= AE \left[1 - \frac{B}{(1 + CE)} \right] & E \geq E_0 = 14.5 \text{ keV} \end{aligned} \quad (6)$$

with the following parameters

$$\left. \begin{aligned} E_0 &= 14.5 \text{ keV} \\ R_{0,Al} &= 9 \cdot 10^{-07} \text{ g/cm}^2 \\ A &= (1.06 \cdot Z^{-0.38} + 0.18) \times 10^{-03} \text{ g/cm}^2 \cdot \text{keV} \\ B &= 0.22 \cdot Z^{-0.055} + 0.78 \\ C &= (1.1 \cdot Z^{-0.29} + 0.21) \times 10^{-03} \text{ g/cm}^2 \cdot \text{keV} \\ E_r &= \frac{E_0}{\left(\frac{AE_0 \left[1 - \frac{B}{(1 + CE_0)} \right]}{G \cdot R_{0,Al}} - 1 \right)^{\frac{1}{F}}} \\ D &= \frac{AE_0 \left[1 - \frac{B}{(1 + CE_0)} \right]}{(E_0 + E_r)^F} \end{aligned} \right\} (7)$$

As can be seen in formula (6) and (7), this model depends on two main parameters (F , G) that must be defined for each different material. These two parameters have been defined for

41 different elements with the help of the ref. [23]. The method of calibration is described in the following section.

C. Parameters of the model

At low energy, below 14.5 keV the Weber expression has been replaced by a simple power law relationship (6) that depends on the two parameters F and G . The power factor F and the critical range $G \times R_{0,Al}$ have been evaluated for 41 different elements, according to the stopping power calculated at low energy by Shinotsuka [23]. For electron energies between 50 eV and 30 keV, Shinotsuka [23] have calculated, with the full Penn algorithm, the stopping power from experimental energy-loss-function data. The CSDA range of these 41 elements has been calculated by integration of the reverse of the stopping power (formula 1). They are presented for 8 different elements in Fig. 7. Both CSDA range and stopping power curves have been used to parameterize the factors F and G for 41 different elements.

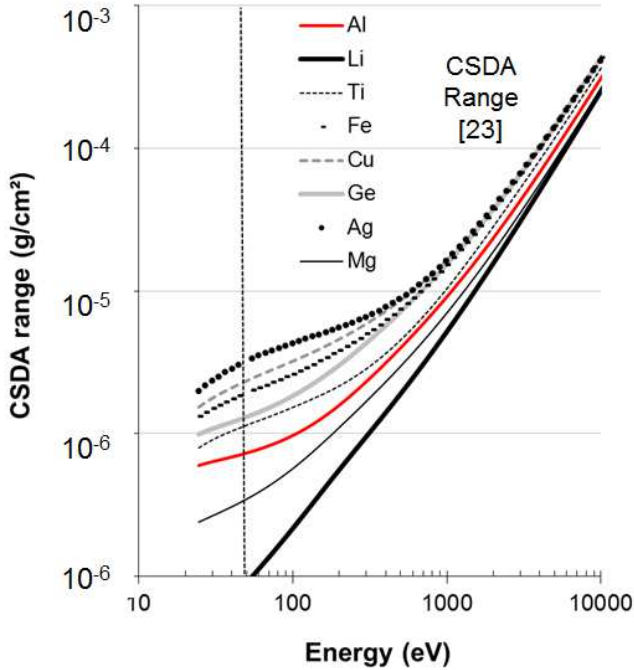


Fig. 7. Electrons CSDA range/energy function calculated with the stopping power of Shinotsuka [19]

According to the CSDA range curves, $G(Z)$ has been defined as:

$$G(Z) = \frac{r_{CSDA,Z}(50eV)}{r_{CSDA,Al}(50eV)}$$

Where $r_{CSDA,Z}$ is the CSDA range of 50 eV electrons in the material Z , and $r_{CSDA,Al}$ is the equivalent range in aluminum. The values are given in table 1 for the 41 elements of the reference [23]. Of course $G = 1$ for aluminum. G represents the CSDA range of a given element relatively to the aluminum. The aluminum has been chosen as a reference material, because it has been extensively studied during the past, and hence many data are available in the literature for this element. The

practical range being assumed to vary similarly to the CSDA range, this factor has been directly applied to the practical range function. This approach has been validated by comparison with the Monte Carlo simulations (fig. 5).

Second, the F factor has been chosen in a way that the derivative of the extrapolated range dx/dE varies, in the energy range [1 keV, 10 keV], in a similar way as the inverse of the stopping power given in ref. [23]. The values of the F factors are also listed for the 41 elements of reference [23] in the table 1. As can be seen in this table, F varies from ~ 1.6 up to 1.8 for Z varying from 3 up to 73. These values remain in the range ($1.3 < \dots < 1.7$) of the standard values used in the literature to fit the experimental range data [7, 16].

Table 1: G and F parameters for the 41 elements of ref. [19].

Z	G	F
3	0.06	1.776
4	0.69	1.758
6	0.76	1.734
11	0.09	1.719
12	0.4	1.714
13	1	1.696
14	0.53	1.696
19	0.14	1.656
21	0.9	1.69
22	1.26	1.67
23	1.69	1.657
24	1.93	1.64
26	2.09	1.636
27	3.1	1.654
28	2.49	1.649
29	2.41	1.634
32	1.64	1.63
39	1.17	1.624
41	3.32	1.599
42	3.86	1.594
44	3.97	1.593
45	3.62	1.599
46	3.31	1.6
47	3.01	1.625
49	2.12	1.601
50	2.67	1.6
55	0.32	1.599
64	1.89	1.6
65	2.13	1.627
66	2.46	1.622
72	4.23	1.575
73	5.97	1.577

As can be seen in Figure 5, for the three tested elements, the analytical expression provides extrapolated ranges in very good agreement with the Monte Carlo simulations of OSMOSEE2.3. The plateau region at low energy is reproduced faithfully for Al, Si and Ag. This validates the approach chosen for the parameterization based on the use of the electron stopping power [23]. However this conclusion shall be

temperated according to the uncertainty within the definition of the practical range at these low energies. From one reference to another, some discrepancies can be observed on the practical range values [19, 24, 25]. This is the case at low energy, where the simulations depend closely on the used mean free path, which can suffer a relatively large uncertainty, especially around some tens of eV, where the inelastic mean free path grows up rapidly. In conclusion, the accuracy of the model is expected to be good down to 50 eV. It could be extrapolated with a fairly good reliability down to 10 eV. But, in any case, below around some tens of eV, the transport of electrons can be assimilated to a random walk motion and the definition of a representative average extrapolated range becomes questionable.

VI. CONCLUSION

An analytic formula for the extrapolated range of electrons in condensed matter is given for 41 elements. The model has been parameterized according to the stopping power provided at low energy in ref. [23]. The range of application of the formula goes from ~10eV up to some tens of MeV. For three different materials (Al, Si, Ag), this model is showed to be in good agreement with the Monte Carlo simulations of the OSMOSEE2.3 code. In the future, the validation shall be consolidated by extension to some other materials.

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