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Anne C. Starley
Utah State University

Lisa M. Phillipps
Utah State University

JR Dennison
Utah State University

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Electron Penetration Range for Diverse Materials

Jane Starley and Lisa Phillips
Mentor: Dr. JR Dennison
USU Materials Physics Group
Utah State University, Logan, UT 84322-4143

Theory

The range of a material describes the maximum distance electrons can travel through said material, given an initial incident energy, before losing the entirety of its kinetic energy. The penetration depth is the resulting depth at which the electrons have come to rest. Two factors affect this range of any given material: the primary energy loss through inelastic and interactions, and secondarily, the loss of energy through electronic interactions or backscattering of electrons.

This idea is illustrated by a Lichtenburg discharge tree, as seen in Figure 1. The tree is an example of a situation where an accelerated high voltage comes to rest and deposits energy at a given range in an insulating material. The side view of the Lichtenburg figure displays the melted plastic caused by the energy of the incident electrons at a uniform penetration depth. Here, the stored charge is dissipated through a discharge.

A model previously developed by the Materials Physics Group predicts the range, 3, and 4, and also describes the effective number of valence electrons, N, in a continuous composite analytic function. This range is used to predict the distribution of incident electrons produced by the space plasma environment, within materials as well as the energy deposited by the electrons as they traverse through material. The range is also used in Electron Beam Theory (Figure 6), the most common form of medical radiography. Obtaining accurate, reliable, and efficient information on the range of electron penetration is, therefore, extremely important to the medical community.

Effects of Parameterization

We initially looked at our single parameter N, as a function of density, mean atomic weight, mean atomic number, plasmon energy or bandgap, conductivity, phase, and more. We fit the information gathered in our analysis, and in hopes of finding strong trends we added one or more of the parameterizations as illustrated in Figure 6.

Applications

The range model developed predicts the penetration depth for various materials and, therefore, extremely important to the medical community.


The range model of energetic electrons into diverse materials can be modeled approximately with a simple fit. This fit is a function of a single parameter, N, which describes the effective number of valence electrons. Using the Continuous Slow-Down-Approximation (CSDA) for energy deposition in a material, a composite analytical formula has been developed which estimates the range of maximum penetration depth of incident electrons for energies from <10 eV to >10 MeV with an uncertainty of ~20%. The fit also incorporates several common properties compiled for each material, including the mean atomic number, mean atomic weight, density, and band gap. However, the model has been fit to existing data for 247 materials collected from the ESTAR and IMPF databases compiled by NIST to determine N values. Comparison of N, with the material properties from this large materials database may lead to the prediction of N, for materials which have no supporting data.

Original Model

A model previously developed by the Materials Physics Group predicts the range, 3, and 4, and has been found to describe the range energy-dependent range, R(E), as a function of incident electron energy for known materials. In a continuous composite analytic function, 3, the range is used to predict the distribution of incident electrons produced by the space plasma environment, within materials as well as the energy deposited by the electrons as they traverse through materials. The range is also used in Electron Beam Theory (Figure 6), the most common form of medical radiography. Obtaining accurate, reliable, and efficient information on the range of electron penetration is, therefore, extremely important to the medical community.


c = 1.2

c = 0.7 ± 0.2

a = 1.1 ± 0.2

Theoretical and experimental results for a variety of materials, and the range for arbitrary materials can be calculated.

Fig. 1. Front (Left) and side (Right) views of a Lichtenburg discharge tree. The white line (Right) indicates the new distribution of charged change a <1 MeV electron beam at 90° to a PMMA sample.

Fig. 2. Range formula for low energy, medium energy, and high energy.

Fig. 3. Formulas for geometric mean energy loss per collision.

Fig. 4. Formulas for plasmon energy.

Fig. 5. Comparison between several range approximations and the data from the ESTAR database for Au. The IMPF data for Au are also plotted along with the TPP-JM IMPF formula for Au.

Table 2. Alumina’s variation in a fitting factor as the bandgap fluctuates.

Future Work

We gratefully acknowledge contributions from the Materials Physics Group. This research was supported through funding from SDL.

References

Future work by the USU Materials Physics Group includes:

- Study fits based on the extended parameters of the material database.
- Develop a user friendly application to calculate the range versus incident energy for all materials in the database and for other arbitrary materials.
- Develop a general formula to predict values for N, and the range for arbitrary materials, based on readily available materials properties.
- Compile findings onto a user friendly website.

To further validate the range approximations and to lead to possible new discoveries in range penetration, the Materials Physics Group’s material database needed to be expanded. A spreadsheet had previously been compiled with information on a number of materials. The spreadsheet’s minor errors were corrected and both the total number materials in the database and parameters for each material were extended. The large number of materials allowed for a more exact fit to be discovered with the CSDA. Adding more parameters offered the opportunity of discovering possible trends that might enable a discovery of an even more exact function to describe the range. Table 1 offers a small selection of the compiled materials, along with some of the materials applicable physical properties.

In order to perform range calculations, a value for the bandgap was needed for each material. While some bandgap ranges were easier to find than others, it was necessary for a comparison to be made to see how much the fitting factor would change with a varying bandgap. These calculations gave desirable results, showing that the fitting factor varied minimally with changing bandgap. For an example, see Table 2, which uses alumina (Al₂O₃) as our chosen material. It was also realized that the error between the values in our calculations and the NIST evidenced values increased as the bandgap’s value increased in distance from the true value.

In order to put the fitting factor variances into perspective, Figure 6 shows what alumina’s fitting factor would look like if we had used a fitting factor of 1.0, 1.42, or 1.82 (the calculated value), and 0.65. Even with a significant variance in the fitting factor, we can expect to find values that are reasonably accurate for most applications.

Table 1. Representative materials and specific material properties.

Table 2. Alumina’s variation in a fitting factor as the bandgap fluctuates.

Fig. 6. Medical radiotherapy.

Fig. 7. Theoretical equation for effective number of valence electrons.

Fig. 3. Formulas for geometric mean energy loss per collision.

Fig. 4. Formulas for plasmon energy.

Fig. 5. Comparison between several range approximations and the data from the ESTAR database for Au. The IMPF data for Au are also plotted along with the TPP-JM IMPF formula for Au (E = 1).

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Fig. 7. Theoretical equation for effective number of valence electrons.