doi:10.1017/S1431927622009333
Microsc. Microanal. 28 (Suppl 1), 2022

Study of Graphene and Thin Foils by a Time-of-Flight Spectrometer for Low Landing Energies

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New technological development and innovations of advanced 2D materials entail high demands on their analysis techniques. A detailed study of electron scattering in solids is essential to the design and diagnostics of next generation materials, as well as in solid-state physics. Inelastic mean free path (IMFP) [1] is a key parameter of electron scattering in both bulk materials and thin foils.

We designed and assembled an ultra-high vacuum scanning low energy electron microscope (UHV SLEEM) equipped with a time-of-flight (ToF) spectrometer [2], which operates in transmission mode, at the Institute of Scientific Instruments of the Czech Academy of Sciences. Both electron microscopy and spectroscopy are powerful tools for obtaining information about the structure and properties of the analyzed materials.

We performed extensive experiments on a monolayer graphene to obtain electron energy-loss spectra (EELS) for low landing energies. Graphene has unique properties, including remarkably high transparency and electrical conductivity, which makes it suitable for studying at very low energies in the transmission mode of UHV SLEEM. We validated our experimental results in two ways. First, they agree with data presented in literature. Second, they are in good agreement with our theoretical results, EELS and band structure, obtained using density functional theory (DFT) and the many-body perturbation theory. We use experimental EELS data to derive effective IMFP [3]. Theoretical approaches to acquire IMFP involve predictive formulas such as TPP-2M [4] or Bethe formula [5] (valid for amorphous materials) and they may also include DFT.

In the following analysis, we focus on the low landing energy interval (200, 800) eV and energy losses up to approximately 40 eV (which covers both π and $\pi+\sigma$ graphene plasmon peaks). The former ensures an overlap with existing IMFP data for comparison purposes (see related references in [3]). Another advantage is that the effect of secondary electrons is reduced in the plasmon part of graphene EELS. The experimental data are presented in Figure 1. Spectral deconvolution with the zero-loss peak (ZLP) was not required because the observed spectral features were already well separated from the ZLP.

Applying the log-ratio method (for details see [3]) on the straight-line segment baseline-corrected energy-loss spectra, we arrived at the effective IMFP values shown in Figure 2. We used theoretical “monolayer thickness” of graphene (i.e. interlayer distance in bilayer graphene) $d = 3.35$ Å as the thickness of the sample in the log-ratio formula. The increase of the IMFP with increasing energy is a direct consequence of the decreasing area of the scaled loss-spectrum, as shown in Figure 1, and the log-ratio formula.

The EELS of free-standing monolayer graphene (Figure 1) obtained from very slow transmitted electrons agree well with theoretical simulations and existing literature, thus confirming the functionality of the UHV SLEEM/ToF device [3].

One of the main advantages of our UHV SLEEM/ToF system is the possibility of using free-standing ultrathin samples. This eliminates the effect of the substrate and it significantly reduces multiple inelastic scattering events. As a result, the analysis of EELS data is greatly simplified. The energy resolution of the ToF spectrometer, 0.5 eV at the landing energy of 50 eV, is more than acceptable for studying a graphene sample and thin foils [6].

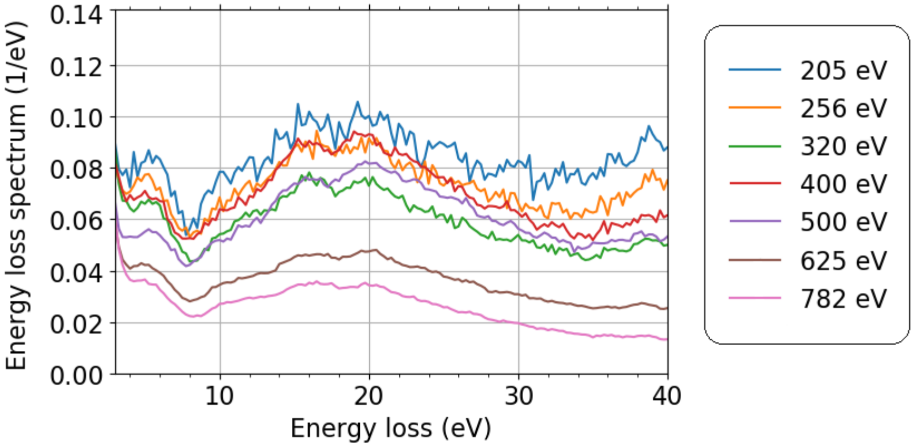

Figure 1. ToF energy-domain spectra with similar values of momentum transfer for selected landing energies. The data are divided by both area of the ZLP and width of energy bin.

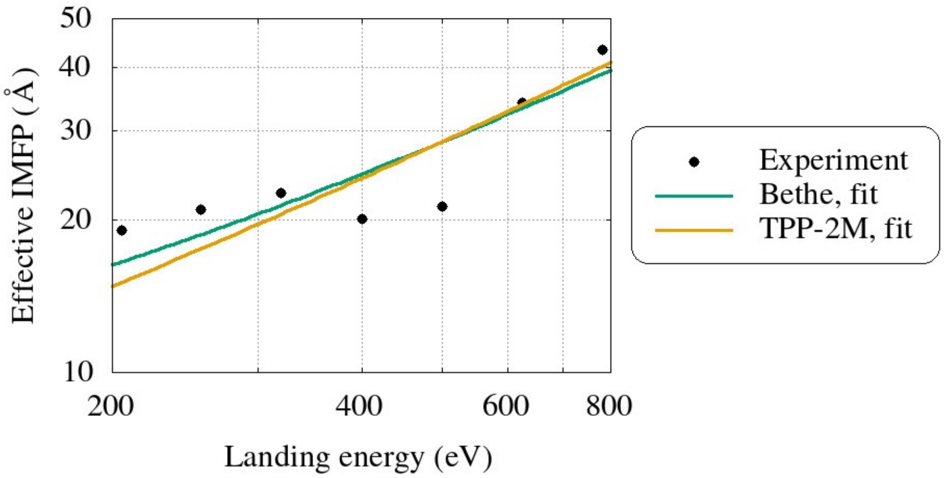

Figure 2. Effective IMFP calculated from the ToF energy-domain spectra compared to effective IMFP derived according to TPP-2M and Bethe formulae.

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[6] This research was funded by the Technology Agency of the Czech Republic, grant number TN01000008 together with institutional support RVO:68081731. Additional support was provided by Strategy AV21, program Breakthrough Technologies for the Future – Sensing, Digitisation, Artificial Intelligence and Quantum Technologies