Stopping cross sections for 0.3–2.5 MeV protons in GaN and InP

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The stopping cross sections of the III–V semiconductor materials GaN and InP for 0.3–2.5 MeV ^{1}H have been studied by the Rutherford backscattering technique. The data are given with an estimated uncertainty better than 2% and the agreement with earlier data existing for InP below 500 keV is good. A commonly used model ZBL-85 predicts the data correctly at the high energy end of our energy interval, but overestimates the stopping values by 7% and 4% for GaN and InP, respectively, at the lower energies. [DOI: 10.1063/1.1337076]

Accurate stopping power values are required for the preparation and modification of materials in semiconductor technologies. Large-band-gap compound semiconductor materials such as GaN have important applications in optoelectronic devices.[1] Various ion beam analytical techniques are frequently used for the characterization of such materials. The depth scales in these techniques follow directly from the stopping powers which are also necessary for deriving the concentration values. Proton stopping powers are of primary importance since they are the basis for the scaling of stopping powers for heavier ions. No previous stopping power data for any ions in GaN exist in the literature. For InP no hydrogen ion data over 500 keV can be found.

The hydrogen ($^{1}H^{+}$) ion beams used in this study were obtained from the 2.5 MV Van de Graaff accelerator of the laboratory. The energy calibration of the beam analyzing magnet was based on the well known $^{19}F(p,\alpha\gamma)^{16}O$, $^{27}Al(p,\gamma)^{28}Si$, and $^{13}C(p,\gamma)^{14}N$ resonance reactions at E_p = 341, 992, and 1747 keV, respectively. Samples of GaN, InP, and Cu (as a reference material) were used in this study. The *n*-type InP ⟨100⟩ sample was Czochralski grown and the wurtzite metalorganic vapor deposition grown ⟨0001⟩ GaN on sapphire was unintentionally *n* type doped. The copper sample used in this study was of 99.97% purity.

The stopping cross sections for protons were determined by the Rutherford backscattering (RBS) technique. The vacuum during measurements was kept better than 5×10^{-6} Pa by placing a liquid nitrogen cooled, large area metal plate close to the sample. The experimental setup used standard electronics, detector, and a beam chopper system. The utilization of a beam chopper system allowed an accurate way by which to normalize the total charge collected. The use of a reference material prevents problems which arise from absolute calibration of the experimental setup, i.e., from determination of the detector solid angle and the number of incident ions. The sample surface normal of the GaN, InP, and Cu was tilted 5° off the beam direction and during measurements the samples were continuously rotated around an axis perpendicular to the sample surface to prevent channeling effects. The scattered ions were detected by a silicon surface barrier detector (thickness of 100 μm and effective area of 40 mm^2) at an angle of 170°. The detector–target distance was 60 mm, corresponding to a detector solid angle of 11.1 msr. The beam chopper count rate was kept constant to maximize the accuracy of the collected charge, corresponding to detector count rates of about 500, 1000, and 650 pulses/s for the GaN, InP, and Cu samples, respectively. The total collected charge per measurement varied between 0.2 and 3 μC for the low and high energies, respectively.

The stopping cross sections of a bulk material can be measured by the RBS method by determining the height H of the backscattering signal.[2] Using the surface energy approximation, the ratio of stopping cross section factors for the sample $[\epsilon_0]$ and reference $[\epsilon_0]^{\mathrm{ref}}$ material is given by

$$\frac{[\epsilon_0]}{[\epsilon_0]^{\mathrm{ref}}}=\frac{H^{\mathrm{ref}}}{H}\frac{\sigma(E_x)}{\sigma(E_x)^{\mathrm{ref}}}, \quad (1)$$

where H and H^{ref} are the heights of the leading edges of the measured signals from the sample and the reference material, and $\sigma(E_x)$ and $\sigma(E_x)^{\mathrm{ref}}$ are the scattering cross sections. E_x is an intermediate energy of the Taylor series expansion of $\epsilon(E)$ in the surface energy approximation

$$E_x=\frac{1/\cos\Theta_1+1/\cos\Theta_2}{K/\cos\Theta_1+1/\cos\Theta_2}KE_0, \quad (2)$$

where K is the appropriate kinematic factor, E_0 the initial beam energy, and Θ_1 and Θ_2 are the incident and exit angles of the beam from the target, respectively. The stopping cross section is then calculated from

$$\epsilon(E_x)=\frac{[\epsilon_0]}{K/\cos\Theta_1+1/\cos\Theta_2}. \quad (3)$$

The leading edge heights of the Ga, In, and Cu backscattering signals were obtained by using a RBS-data analysis computer program.[3] With the program it is possible to accurately fit the plateau of a wide RBS signal when the correct detector geometry, energy resolution, energy/channel calibration, and offset are given. The leading edge height is then obtained from the program when convolution of the theoretical signal by the system resolution is omitted. In this process the stopping powers used by the program do not have any effect on the leading edge heights obtained. Only

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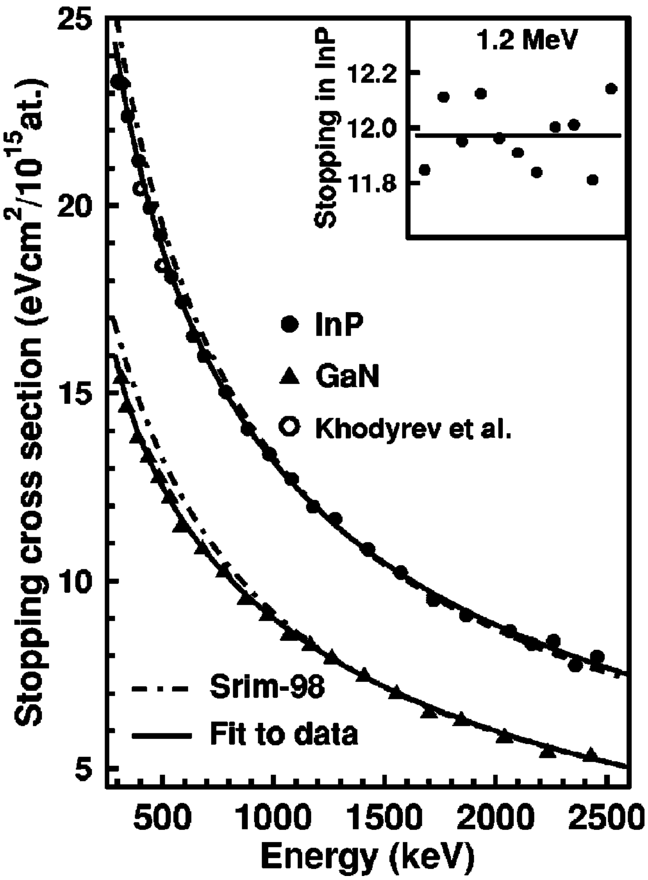

FIG. 1. Stopping cross sections of GaN and InP for protons. The inset shows the scatter in the stopping cross sections for repeated measurements at the proton energy of 1.2 MeV in InP.

the Ga and In signals were used due to the large uncertainties in determining the N and P signal heights, thus the right-hand side of Eq. (1) is divided by a factor of 2.

In the present work the reference stopping cross sections of copper from Refs. 4 and 5 were used. For copper several experimental hydrogen stopping cross section studies are found in the literature in the relevant energy region. For hydrogen ion energies below 1 MeV the data considered most reliable were chosen in Ref. 4 to be utilized as reference values. The experimental stopping cross sections of copper were fitted[4] using a function of the form[6]

$$\frac{1}{\epsilon(E)}=a_0+a_1E^{-0.4}+a_2E^{0.25}+a_3E^{0.8}, \tag{4}$$

with the coefficients $a_0=-0.292\,721\times10^{-1}$, $a_1=0.256\,89$, $a_2=0.871226\times10^{-2}$, and $a_3=1.7585\times10^{-4}$. The fit has an accuracy of about 1%. Above 1 MeV, Eq. (4) was used in Ref. 5 to fit the copper data points from the studies by Luomajärvi[7] and by Andersen *et al.*[8] The fitting coefficients $a_0=-2.5899\times10^{-1}$, $a_1=1.3907$, $a_2=4.0561\times10^{-2}$, and $a_3=0.929\,71\times10^{-4}$ were obtained[5] to calculate stopping cross section values in copper for energies above 1 MeV. The presently chosen low (under 1 MeV) and high reference stopping cross sections in Cu are identical in the energy region of 800–2000 keV.

The present experimental stopping cross sections of GaN and InP calculated using Eqs. (1)–(3) together with the few experimental points in InP by Khodyrev *et al.*[9] and the semiempirical[10,11] values are illustrated in Fig. 1. It can be seen that the statistical errors are small and that the agreement of the stopping cross sections with the scant earlier data is good. For both GaN and InP the semiempirical predictions are consistent with the data at energies over 1 MeV. Below 1 MeV the experimental values systematically fall below those predicted by the ZBL-85 semiempirical model (SRIM-98, SRIM-2000)[10] which overestimates the data by about 7% and 4% for GaN and InP, respectively. The experimental data in Fig. 1 are described well by Eq. (4) with fitting coefficients $a_0=2.3083\times10^{-1}$, $a_1=-7.3477\times10^{-1}$, $a_2=-3.1790\times10^{-2}$, and $a_3=4.1968\times10^{-4}$ for GaN, and $a_0=1.1759\times10^{-2}$, $a_1=-2.3140\times10^{-2}$, $a_2=3.7002\times10^{-3}$, and $a_3=1.7822\times10^{-4}$ for InP. The standard deviations of the fits from the experimental points are about 0.10 and 0.12 $eVcm^2/10^{15}$ at. for GaN and InP, respectively.

The total uncertainties in our stopping cross section data consist of statistical errors in the backscattering measurements and possible systematic errors including, e.g., the uncertainties in the reference stopping cross section. The uncertainty of the resulting stopping cross sections is estimated not to exceed 2%.

The statistical errors in determining the present experimental stopping cross sections of GaN and InP fall below 1%. These uncertainties include the measurement of the leading edge heights H, Eq. (1), of the Ga, In, and Cu signals and normalization of the number of incident ions. The scatter of repeated stopping cross section measurements at 1.2 MeV for InP is shown in the inset of Fig. 1.

Because of the relative measurements, many of the systematic errors cancel out. A few, however, should be considered. The possible uncertainties of the reference stopping cross sections of Cu for H were given in Refs. 4 and 5 as 1%. To check for the possible effect of channeling to the leading edge heights, an amorphized InP sample[12] was prepared by implanting 10^{15} In/cm^2 (at 120 keV) and 10^{15} P/cm^2 (at 100 keV) into the InP sample surface. By comparing the leading edge heights obtained by 5° tilting and continuous rotation of the crystalline and amorphized samples, the effect of channeling was found to be less than the statistical uncertainty ($\leqslant$ 1%). For the present energies, the accuracy of the data evaluation procedure using Eqs. (2) and (3) (Ref. 13) is estimated as better than 1%. The influence of the nonlinear detector response (e.g., Ref. 14 and references therein) was found to be negligible.

To conclude, stopping cross sections of GaN and InP for hydrogen ions are presented. Recent semiempirical models (SRIM-98, SRIM-2000)[10] reproduce well the stopping cross sections at energies higher than 1 MeV. For energies below 1 MeV the stopping cross sections of both GaN and InP are about 4%–7% smaller than the predicted values.

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