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Determination of the electron–hole pair creation energy for semiconductors from the spectral responsivity of photodiodes

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Abstract

Ionizing radiation can be detected by the measurement of the charge carriers produced in a detector. The improved semiconductor technology now allows detectors operating near the physical limits of the detector materials to be designed. The mean energy required for producing an electron–hole pair, W, is a material property of the semiconductor. Here, the determination of W from the spectral responsivity of photodiodes is demonstrated. Using spectrally dispersed synchrotron radiation, different types of semiconductor photodiodes have been examined in the UV-, VUV-, and soft X-ray spectral range. Their spectral responsivity was determined with relative uncertainties between 0.4% and 1% using a cryogenic electrical-substitution radiometer as primary detector standard. Results are presented for silicon n-on-p junction photodiodes and for GaAsP/Au Schottky diodes at room temperature. The investigations for silicon covered the complete spectral range from 3 to 1500 eV, yielding a constant value $W = (3.66 \pm 0.03)$ eV for photon energies above 50 eV, a maximum value of $W = 4.4$ eV at photon energies around 6 eV, and a linear relation $W = h\nu$ (one electron per photon) for photon energies below 4 eV. For GaAsP, we obtained a constant value of $W = 4.58$ eV in the photon energy range from 150 to 1500 eV, with a relative uncertainty of 1–3%, depending on the photon energy.

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1. Introduction

Semiconductor detectors are of growing importance in many fields such as X-ray astronomy, X-ray microscopy and spectroscopy, lithography, and radiometry. The detection principle is that the absorbed energy produces non-equilibrium charge carriers, which are measured. The improved detector technology now allows devices with a sensitivity or pulse height and resolution near the physical limits given by the properties of the semiconductor materials to be realized. The mean energy required for producing an electron–hole pair, W, is such a basic material property of a semiconductor which could depend on the nature of the particle to be detected and its energy.

For energy-dispersive detectors, the mean height of the output pulses for incident monochromatic photons of energy $h\nu$ is, in the absence of any charge losses, proportional to $h\nu/W(h\nu)$, i.e. W could be determined by pulse-height measurement

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('pulse-height method'). On the other hand, any losses being neglected, the spectral responsivity s of photodiodes is given by $s = e/W$, with e being the elementary charge, i.e. W could also be determined from the spectral responsivity ('photocurrent method').

The pulse-height method has the advantage that the number of incident photons need not be determined and that the measured spectrum can be used to identify events with incomplete energy absorption or charge collection. It has been used to derive values for W for high-energy photons and particles. For the two most important solid-state detector materials, silicon and germanium, values for W for α, β and γ radiation with energies of about $100 - 1$ MeV are, e.g., reported in Refs. [1–3]. For silicon, Ref. [1] recommends $W = 3.62(2)$ eV for α and $W = 3.68(2)$ eV for β (and γ) radiation in accordance with, e.g., Ref. [3], while Ref. [2] reports $W = 3.6325(25)$ eV for α and $W = 3.6310(25)$ eV for β (and γ) radiation. These values are generally accepted and used down to energies of a few keV.

With the expansion of the usable spectral range of energy-dispersive silicon detectors down to photon energies of only a few hundred eV, investigations of the photon energy dependence of W for these low energies were needed. As the number of created electron–hole pairs decreases with the photon energy, it had to be found out for which number of electron–hole pairs, or which photon energy, respectively, the discrete nature of the ionization process influences W.

Fraser et al. [4] calculated W for silicon for photon energies in the range from 50 eV to 8 keV, and predicted a decrease of W with increasing photon energy and discontinuities of about 5% and 0.5% at the L- and K-absorption edges, respectively, similar to recent results for the mean electron–ion pair creation energy in the gas phase of xenon [5]. Experimental values for the energy dependence of W in the soft X-ray region, agreeing with the model of Fraser et al., were derived from CCD detectors using the pulse-height method [6–8]. The measurements in Ref. [6,7], however, covered only the energy range above 350 eV and were normalized to the asymptotic value of W at the high-energy data points. In Refs. [8] only a few emission line energies were used, so no data in the vicinity of the silicon L-edge at 99.6 eV were available and the experimental uncertainties did not completely exclude that W could be constant.

This lack of experimental data mainly results from a limitation of the pulse-height method to photon energies above 100 eV for silicon due to the finite energy resolution of the detectors presently available. Furthermore, the large relative peak width masks any line shape artifacts due to incomplete charge collection. A potential shift of the peak position towards lower energies due to incomplete charge collection therefore is practically not detectable by changes of the lineshape [9]. Hence, the conclusion that incomplete charge collection is not significant [8,10] because the peak has a Gaussian shape might be wrong. Moreover, even if incomplete charge collection is accounted for, as in Refs. [6,7], the results critically depend on the model chosen to describe the line shape, as was demonstrated in Ref. [11] for the silicon K-absorption edge. Finally, the determination of W from the pulse-height spectra requires calibration of the pulse-heights in units of the elementary charge which at present is possible only by normalization to W at higher energies which therefore must be known independently.

Using the photocurrent method, W is determined from the integrated detector output, measured either as accumulated charge or as ionization current, for a known flux of incident photons of known energy. This method has the advantage that the number of incident photons can be increased to achieve an output signal which is so high that it can be measured. That offers the possibility of using this method also for very low photon energies, at which the (energy-dispersive) detection of single photons is not possible. Especially, photon energies well below the silicon $L_{2,3}$ edge are accessible.

We used the photocurrent method to determine $W(h\nu)$ for silicon in the soft X-ray region from the spectral responsivity $s(h\nu)$ of photodiodes. The spectral responsivity was determined by comparison of the response of the photodiode to the response of a cryogenic electrical-substitution radiometer (CESR) as primary standard for radiant power measurements [12]. Using a CESR for the first time allowed $W(h\nu)$ to be determined

accurately by this method [13,14]. A constant value 3.66 ± 0.03) eV was derived down to photon energies of 50 eV.

However, since in the lower photon energy limit between the band gap and twice its value, i.e. below 2.2 eV, exactly one electron–hole pair is created independently of the photon energy, a change from a constant value to a photon energy depending function $W(h\nu)$ must occur somewhere below 50 eV. Knowing the number of impact ionizations by energetic electrons and the initial distribution of the kinetic energies of the photo-excited charge carriers, the total number of electron–hole pairs created by the absorption of a photon, i.e. the quantum yield $\eta = h\nu/W(h\nu)$, can be calculated. Calculation of W for photon energies below 2.5 keV [13,14] suggests a constant W for photon energies as low as 20 eV. The above-mentioned break-down of the proportionality between η and $h\nu$ should therefore occur at photon energies of only a few times the fundamental band gap energy. At the moment, this photon energy range is experimentally accessible exclusively by the photocurrent method.

In this paper we present the determination of W for Si in the UV and VUV spectral range and for GaAsP in the soft X-ray spectral range by the photocurrent method. The contributions to the relative uncertainty are discussed and the limitations of the method are indicated.

2. PTBs detector calibration facilities at BESSY I

To determine $W(h\nu)$ from the spectral responsivity of a photodiode, the availability of a high-accuracy detector standard is essential. In this section, we describe our experimental setup for accurate measurements of the spectral responsivities.

The operation principle of a CESR is the transformation of the incident radiant power Φ into a heat flow directed through a heat link to a heat sink of constant temperature. If operating the CESR in the dynamic substitution mode, the absorber temperature is controlled by electrical heating as well and the radiant power equals the change in electrical heater power when opening the radiation shutter. Details of the operation of the CESR are given in Refs. [12,15,16]. The relative uncertainty for the measurement of a radiant power of about 1 μW is about 0.4%. A critical effect might be the loss of radiant power to the creation of radiation damage at the absorber cavity, see Ref. [12]. By direct comparison of the CESR to the primary source standard BESSY I [17], this loss was determined to be below 0.2%, i.e. below the relative uncertainty of this measurement.

At the PTBs Radiometry Laboratory at the electron storage ring BESSY I, a soft X-ray beamline as well as a normal incidence beamline are designed for detector calibration with monochromatized radiation in the spectral ranges from 40 to 1500 eV [18], and from 3 to 35 eV [12,15,16], respectively. The relative spectral bandwidth varies between 0.1% and 0.7% for the soft X-ray beamline and between 1% and 2% for the normal incidence beamline. The influence of the monochromator bandwidth on the measurement of s is, however, rather weak because within the bandwidth s is almost constant for the photodiodes investigated here [12]. For the soft X-ray beamline, metal filters are used to suppress higher diffraction orders to below 1% [18] and for the normal incidence beamline edge-filters (WG305, SiO_2 and MgF_2), see Fig. 10 of Ref. [12]. The long-wavelength scattered light contribution is below 0.2% [12].

As the stored electron current monotonically decreases with time, the radiant power behind a monochromator is not stable and a comparison between two detectors will be possible only if the radiant power is monitored. We used the stored electron current as the monitoring signal for the soft X-ray beamline [19] and SiO_2 and MgF_2-beamsplitter were used to get a monitor signal at the normal incidence beamline [12].

3. Determination of $W(h\nu)$ from the spectral responsivity of photodiodes

W can be obtained from the spectral responsivity of a photodiode by $W = es_r/s$. The dimensionless factor s_r is defined as the ratio of the spectral responsivity of the diode under test to the spectral responsivity of an 'ideal' diode ($s = e/W$) which is

not affected by any loss process, such as reflection, absorption in insensitive surface layers (passivating oxide), escape of fluorescence radiation or of electrons, or the recombination of electron–hole pairs before they are collected at the electrodes. s_r is hereinafter called "relative responsivity".

3.1. Measurement of the spectral responsivity of photodiodes

The detectors used were 10 mm × 10 mm silicon photodiodes with a shallow n-conducting front region on top of a p-type epitaxial layer of 35 μm thickness on a 200 μm p^+-substrate (AXUV100G from Intern. Rad. Detect.), passivated with a nitrided oxide (4.3 nm thick) for high radiation hardness [20] as well as 10 mm × 10 mm $GaAs_{0.63}P_{0.37}$/Au Schottky diodes (G2119 from Hamamatsu).

The spectral responsivity of these diodes was measured at room temperature at the soft X-ray detector calibration facilities of PTB for the UV/VUV and soft X-ray spectral ranges, respectively. The signal current of the diode was measured with a Keithley 617 electrometer. The radiant power was measured using the CESR.

At the soft X-ray beamline, the CESR was aligned behind a cooled aperture, 3 mm in diameter. The diode was mounted on a linear feedthrough and placed behind the same aperture for the measurement of the photocurrent. The measured spectral responsivity for the different types of diodes is shown in Fig. 1. For the silicon diodes, it varies by less than 15% over the soft X-ray spectral range. The influence of stray light and higher diffraction orders (about 1%) is therefore below 0.2%. For the GaAsP/Au Schottky diode, the spectral responsivity varies by a factor of 2 between 80 and 150 eV, increasing the contribution of diode signal by second-order photons to up to 2% in that spectral range. The typical relative uncertainty of the spectral responsivity was 0.4% (1σ) for the silicon diodes and 1% for the GaAsP/Au diodes.

At the normal incidence beamline, the absorber cavity of the CESR was removed from the beam and the diode placed at the same position as the cavity. This was necessary because of the larger divergence of the refocused photon beam of about 12 mrad, compared to only 2 mrad at the soft X-ray beamline. Details of these measurements are presented elsewhere [21]. For the normal incidence monochromator, no higher diffraction orders were detected in the spectral range used here.

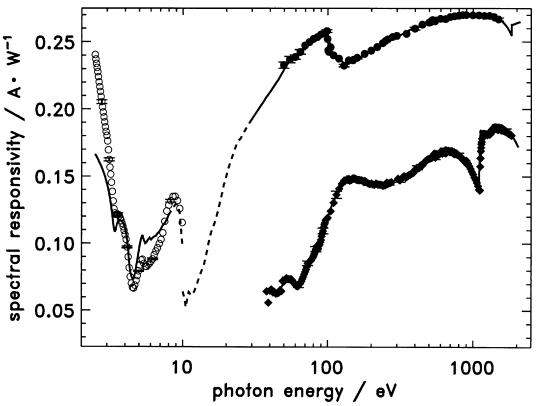

Fig. 1. Spectral responsivity of an n-on-p silicon photodiode in the soft X-ray region (closed circles) and UV and VUV region (open circles) and for a GaAsP/Au Schottky diode in the soft X-ray region (diamonds) measured against the CESR. Typical experimental uncertainties are indicated. The lines are calculations of the spectral responsivity using Eq. (1) with the parameters determined from the angle dependence measurement Fig. 4 and a constant value $W = 3.66$ eV for Si and $W = 4.58$ eV for GaAsP.

3.2. Description of the relative responsivity of photodiodes

The determination of $W = es_r/s$ requires a method to determine s_r. Due to the high attenuation coefficient for photons in the soft X-ray spectral region, the magnitude of s_r is mainly determined by the photoabsorption in the front layer and by charge recombination effects at the front layer semiconductor interface. s_r can be written as [14]

$$s_r/(1-\rho) = (1-\alpha_{ox})[1-\varepsilon_f(r_i, l_{th}) - \varepsilon_b(d_d, d, \varepsilon_{end}) - \varepsilon_p - \varepsilon_s] + \varepsilon_{ox} \quad (1)$$

ρ is the reflectance and α_{ox} is the absorptance of the front layer (silicon oxide or gold. The terms ε_i (i = f, b, p, s, ox) represent the individual contributions of the different loss processes. ε_f describes the recombination loss at the front layer interface, parameterized by a charge carrier reflection probability

at the interface, r_i, and a thermalization length l_{th}. The photon transmission loss ε_b is a function of the depth of the completely depleted region, the thickness of the sensitive layer d_i (e.g. the low-doped epitaxial layer for the silicon diodes investigated here) and the collection efficiency ε_{end} at the bottom of the sensitive layer. ε_p and ε_s are the photon and electron escape losses, while ε_{ox} is the contribution of electrons originating from the front layer. For details of this model, see Ref. [14].

The front layer transmittance $\tau_{ox} = (1 - \rho)(1 - \alpha_{ox})$ is the dominant contribution in Eq. (1) (see Fig. 3). The data used for the front layer attenuation coefficient therefore are of crucial importance. For the silicon diodes, we determined the oxide thickness and absorption coefficient from reflection measurements in the 50–200 eV spectral range [22].

For the GaAsP/Au diodes this method for the determination of the front layer absorptance failed due to the roughness of the surface. We determined the absorption coefficient of Au, whose fine structure is not correctly reproduced by the atomic scattering factors of Ref. [23], by a measurement of the transmittance of a thin Au-layer supported by a thin polyimide foil, compared to the transmittance of the uncoated foil. As we did not know the area mass density of the coating with sufficient accuracy, we normalized our results in the energy region from 350 to 540 eV, which shows no fine structure, to the atomic scattering factors of Ref. [23] (see Fig. 2).

The next dominant contribution to s_r is the recombination loss ε_f (shown together with ε_b in Fig. 3). For the GaAsP/Au diode ε_b becomes also significant in the photon energy range between 700 eV and the Ga-$L_{2,3}$ edge at 1116 eV. The remaining terms are only small corrections. ε_s and ε_{ox} contribute about 1% and are almost equal so that they cancel each other, except for photon energies below 100 eV in the case of the silicon diodes (see Fig. 3). ε_p is negligible in the spectral region investigated here (below the silicon K-edge).

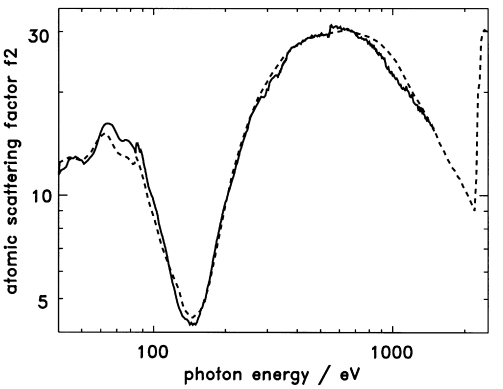

Fig. 2. Atomic scattering factor f2 for gold from 40 eV to 1500 eV, determined from the transmittance of a thin gold layer, solid line. The thickness of the layer was determined such that the experimental values agree at photon energies between 350 eV and 540 eV with the scattering factors of Ref. [23], dashed line.

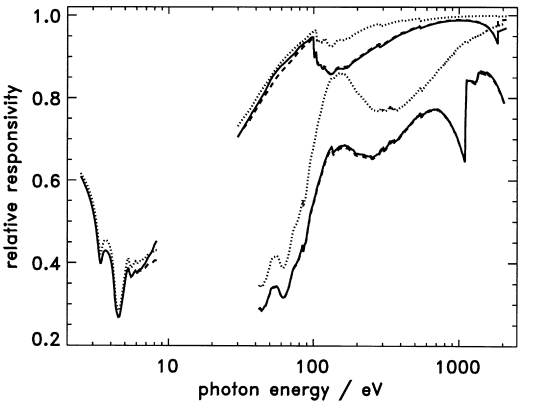

Fig. 3. Calculation of the relative responsivity by Eq. (1) for an n-on-p silicon photodiode in the UV-, VUV-, and soft X-ray range (data below 10 eV and upper three curves in the soft X-ray range) and a GaAsP/Au Schottky diode in the soft X-ray range (lower three curves): only front layer transmittance, τ_{ox}, (points), including the effects of the charge collection efficiency, $\tau_{ox} \cdot (1 - \varepsilon_f - \varepsilon_b)$, (dashes), nearly coincident with the final result including the electron and photon escape losses (solid line).

3.3. Experimental determination of the relative responsivity

The ratio of the measured response for radiation at 60° incidence to the normal of the diode and at normal incidence, $s_\Theta = s(60°)/s(0°)$, is used to determine s_r as described in Refs. [14,24]. s_Θ is shown in Fig. 4 with the best fit of Eq. (1), using d_d, d, ε_{end}, l_{th}, and r_i as fit parameters. Note that there is no cross-correlation between parameters l_{th} and r_i for

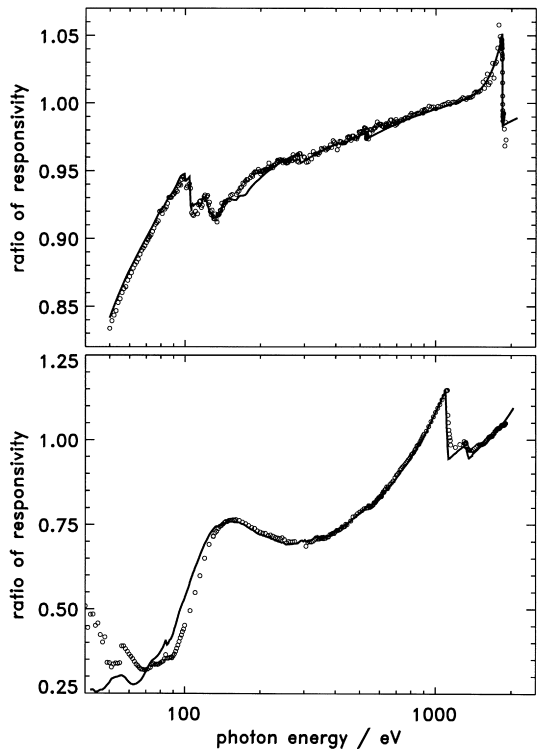

Fig. 4. Measured ratio of the spectral responsivity of an n-on-p silicon photodiode (upper part) and a GaAsP/Au Schottky diode (lower part) at 60° to the responsivity for normally incident radiation (symbols) and calculation with the best fit parameters for Eq. (1) (solid line).

ε_f on the one hand and d, d_d and ε_{end} for ε_b on the other, because ε_f is significant only for low-energy photons, absorbed close to the surface, while ε_b dominates for higher photon energies, where ε_f is close to zero.

For the silicon diode, a carbon surface contamination, identified by an absorption edge at 280 eV and confirmed by the reflection measurements, was also taken into account. The best-fit parameters are a 0.5 nm carbon layer, $d_d = 5$ μm, $d = 47$ μm, $\varepsilon_{end} = 85\%$, $l_{th} = 150$ nm, and $r_i = 84\%$. A detailed discussion of these results is given in Ref. [14]. The typical relative uncertainty in the determination of s_r is about 0.5–1% for these silicon diodes in the soft X-ray region. This must be seen in the context that s_r deviates from unity by only up to 15%. For the GaAsP/Au diodes, however, s_r varies between 30% and 85%. The exact determination of s_r therefore is more critical. The best fit was achieved with a front layer consisting of 8.5 nm of gold and an insensitive layer of 2 nm of GaAsP. ε_f is described by $r_i = 0\%$ and $l_{th} = 30$ nm, ε_b by $d_d = 0.23$ μm, $d = 3$ μm, and $\varepsilon_{end} = 20\%$. Carbon contaminations could not be detected. For photon energies below 150 eV, the agreement between fit and measurement is poor. This can be explained by the high absorptance α_{ox} of the gold front layer. While for normally incident radiation α_{ox} varies between 50% and 60% for photon energies below 80 eV, this value increases to 75–85% for incidence at 60°. This may lead to a failure of our model for describing ε_{ox}. For silicon n-on-p diodes, it was reported that about 20% of the energy absorbed in the oxide contributes to the diode signal in the photon energy region around 10 eV [25,26]. Our calculation, however, tentatively yields that ε_{ox} and ε_s cancel each other for materials of an almost equal absorption coefficient, as, e.g., an Au/GaAsP dead layer on top of GaAsP, or silicon oxide on silicon around 10 eV photon energy, due to a balance between electron transport from the front layer into the substrate and vice versa. This is due to the fact that the interface potential barrier has been neglected in the calculation of ε_{ox} and ε_s in Ref. [14]. For photons with energies below 80 eV, the approximation of Canfield et al. [25] and Saite and Onuki [26] yields $\varepsilon_{ox} = 0.16$ almost equal to $1 - \alpha_{ox} = 0.2$ thus being no longer a small correction. However, at normal incidence, still $\varepsilon_{ox} = 0.1 \ll 1 - \alpha_{ox} = 0.5$ is valid. This may explain the rather good agreement between measurement and model according to Eq. (1) as shown in Fig. 1, while the fit of Eq. (1) to s_Θ (Fig. 4) failed below 150 eV. At the moment this lack of an adequate model for ε_{ox} in the case of high values of α_{ox} is the most significant restriction to our method for determining s_r.

To estimate the uncertainty for the modeling of s_r, the thickness d_{Au} of the Au-layer and the parameters r_i and l_{th} were varied, as was done before for the silicon diodes [14]. The thickness d_{Au} could be determined with low uncertainty when the measured fine structure of the absorption coefficient (see Fig. 2) was used. The thickness could be varied from 8.5 to 8.7 nm within the experimental

uncertainty of s_Θ yielding a decrease of s_r by 0.6%. For l_{th} a possible variation from 30 to 32 nm yields a decrease of s_r by 1% below 300 eV and about 0.5% above 300 eV. r_i could be varied from 0% to 5%, yielding an increase in s_r by 1.5% below 300 eV and about 0.5% elsewhere.

The uncertainties of s_r for the GaAsP/Au diodes can thus be called rather high below 150 due to the unknown influence of ε_{ox}. The fundamental problems outlined above do not allow at the moment to give a reasonable number. Between 150 and 300 eV the uncertainty is dominated by the uncertainty of ε_f and amounts to 2%, above 300 eV it is dominated by the uncertainty of α_{ox} and amounts to 1%. Above 1116 eV, the energy of the Ga-$L_{2,3}$ edge, the uncertainty increases to about 3%, estimated from the deviation between the fitted and measured values of s_Θ. Again, the problem is the proper description of the electron losses ε_s.

3.4. Experimental values of $W(h\nu)$ for Si and GaAsP

The values for the electron–hole pair creation energy in GaAsP and silicon obtained from s and s_r are shown in Fig. 5.

We obtained a constant value of $W = 4.58$ eV for GaAsP. The typical uncertainties are rather high below 150 eV, 2.3% from 150 to 300 eV, 1.5% between 300 and 1116 eV, and 3% above the Ga-$L_{2,3}$ edge at 1116 eV. The uncertainty of W is dominated by the uncertainty in the determination of s_r, which is discussed above. This is correlated with the significant absorptance of the gold front layer of the Schottky diodes investigated here. There are, however, at the moment no GaAsP p–n-type diodes with a sufficiently shallow top layer available.

For silicon in the VUV spectral range, the problems are very similar to those for GaAsP in the soft X-ray range, because even the very thin oxide layer of the diodes of about 4 nm starts to absorb strongly above about 7 eV and around 10 eV α_{ox} exceeds 50%. First results could therefore be obtained only in the region in which the oxide is transparent. For higher photon energies, α_{ox} and ε_{ox} could not yet be determined with sufficient accuracy. The reflectance ρ was measured, and the other parameters in Eq. (1) could be determined from the measurements

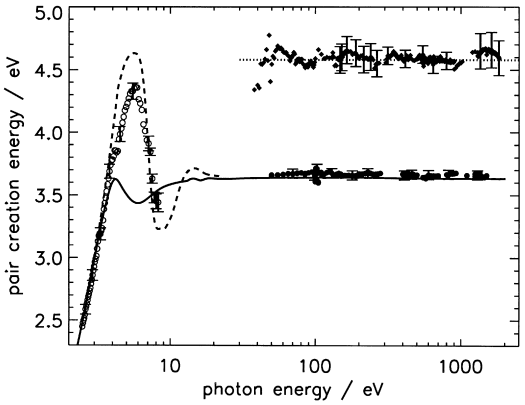

Fig. 5. Mean energy W required for creating an electron-hole pair determined from s_r and s: for silicon in the soft X-ray region [14] (closed circles) and UV and VUV region [21] (open circles) and for GaAsP in the soft X-ray region (diamonds). Typical experimental uncertainties are indicated. For silicon, calculations from Ref. [14] are shown as solid line and dashed line (see text). The points indicate the mean value of 4.58 eV for GaAsP.

in the soft X-ray region. By the parameters r_i and l_{th}, ε_f can be calculated as a function of the absorption coefficient. ε_b can be treated in the same way and is not significant for VUV photon energies. α_{ox} is close to zero in the energy region investigated here. First results for the electron–hole pair creation energy in silicon in the VUV spectral range obtained by the photocurrent method [21] are shown together with the values for the soft X-ray range [13,14]. Additionally shown is a calculation of W from Ref. [14] (solid line). The measured values of W in the VUV range spectral range are close to a calculated "upper limit" for W [14], shown as dashed line in Fig. 5. Although there is still a gap in the data between 8 and 50 eV, we are confident that further measurements by the photocurrent method, which are now underway, will allow the calculation of W to be experimentally verified.

4. Summary and conclusion

We determined the mean energy required for creating an electron–hole pair in a semiconductor

from the spectral responsivity of photodiodes by the photocurrent method. The photon energy region in which this method can be applied is much wider than the range accessible by the pulse-height method, because is does not require the energy-dispersive detection of single photons. That offers the possibility of using this method also for very low photon energies. The only limitations arise from the quality of the semiconductor photodiodes available.

GaAsP/Au Schottky diodes have been used to determine $W(h\nu)$ for GaAsP in the spectral region from 150 to 1500 eV with relative uncertainties from 1.5% to 3%. Due to the strong absorption of up to 50% in the diodes gold-Schottky contact, the values obtained below 150 eV have a rather high uncertainty. The data presented here are the first experimental values for W of GaAsP in the soft X-ray range. The availability of diodes with a less absorbing front layer would allow to decrease the uncertainty of W, as it was demonstrated for silicon with uncertainties of about 1% down to 50 eV [14].

Values of $W(h\nu)$ for silicon could be determined in the energy region below 8 eV, where the oxide passivation layer is sufficiently transparent. Although the spectral range from 3 to 1500 eV is not yet completely covered by our measurements, the results are clearly in favor of our recent calculation of W (solid line in Fig. 5) [14], while the earlier calculations of Ref. [4] and the conclusions drawn from pulse-height measurements in the soft X-ray range [6–8] are not consistent with our results.

We conclude that the determination of the mean energy required for creating an electron–hole pair in a semiconductor from the spectral responsivity of photodiodes by the photocurrent method is a well-suited approach for spectral regions, in which the pulse-height method cannot be applied due to the noise of energy-dispersive detectors.

References

[1] ICRU Report 31, ISBN 0-913394-25-4, 1979.
[2] R.D. Ryan, IEEE Trans. Nucl. Sci. NS-20 (1973) 473.
[3] R.H. Pehl, F.S. Goulding, D.A. Landis, M. Lanzlinger, Nucl. Instr. and Meth. 59 (1968) 45.
[4] G.W. Fraser, A.F. Abbey, A. Holland, K. McCarthy, A. Owens, A. Wells, Nucl. Instr. and Meth. A 350 (1994) 368.
[5] C. Butz Jörgensen, C. Oelsen, H.W. Schnopper, T. Lederer, F. Scholze, G. Ulm, Nucl. Instr. and Meth. A 367 (1995) 83.
[6] P. Lechner, L. Strüder, Nucl. Instr. and Meth. A 354 (1995) 464.
[7] P. Lechner, R. Hartmann, H. Soltau, L. Strüder, Nucl. Instr. and Meth. A 377 (1996) 206.
[8] R.P. Kraft, D.N. Burrows, G.P. Garmire, J.A. Nousek, J.R. Janesick, P.N. Vu, Nucl. Instr. and Meth. A 361 (1995) 372.
[9] F. Scholze, G. Ulm, Nucl. Instr. and Meth. A 339 (1994) 49.
[10] A. Owens, G.W. Fraser, A. Keay, A. Wells, K.J. McCarthy, S.F. Hill, E.A. Hughes, A.D. Smith, V. Suller, M. Surman, X-Ray Spectrom. 25 (1996) 33.
[11] K. Torii, H. Tsunemi, E. Miyata, K. Hayashida, Nucl. Instr. and Meth. A 361 (1995) 364.
[12] H. Rabus, V. Persch, G. Ulm, Appl. Opt. 36 (1997) 5421.
[13] F. Scholze, H. Rabus, G. Ulm, Appl. Phys. Lett. 69 (1996) 2974.
[14] F. Scholze, H. Rabus, G. Ulm, J. Appl. Phys. 84 (1998) 2926.
[15] A. Lau-Främbs, U. Kroth, H. Rabus, E. Tegeler, G. Ulm, Rev. Sci. Instr. 66 (1995) 2324.
[16] A. Lau-Främbs, U. Kroth, H. Rabus, E. Tegeler, G. Ulm, B. Wende, Metrologia 32 (1995/96) 571.
[17] D. Arnold, G. Ulm, Rev. Sci. Instr. 63 (1992) 1539.
[18] F. Scholze, M. Krumrey, P. Müller, D. Fuchs, Rev. Sci. Instr. 65 (1994) 3229.
[19] H. Rabus, F. Scholze, R. Thornagel, G. Ulm, Nucl. Instr. and Meth. A 377 (1996) 209.
[20] R. Korde, J.S. Cable, L.R. Canfield, IEEE Trans. Nucl. Sci. NS-40 (1993) 1655.
[21] P. Kuschnerus, H. Rabus, M. Richter, F. Scholze, H. Werner, G. Ulm, Metrologia 35 (1998) 355.
[22] F. Scholze, H. Rabus, G. Ulm, Proc. SPIE 2808 (1996) 534.
[23] L. Henke, E.M. Gullikson, J.C. Davis, At. Data Nucl. Data Tables 54 (1993) 181 and actualized values for gold accessible at http://www-cxro.lbl.gov:80/optical_constants/
[24] M. Krumrey, E. Tegeler, Rev. Sci. Instr. 63 (1992) 797.
[25] L.R. Canfield, J. Kerner, R. Korde, Appl. Opt. 28 (1989) 3940.
[26] T. Saito, H. Onuki, Metrologia 32 (1995/96) 525.