of deep level impurities using the known capacitance transient measurement techniques. The circuit employs five integrated circuits and one transistor and requires only a + 5 volts supply. The pulse generator can be of any commercial model suited to the user that provides facilities for external triggering. In the circuit that we have developed pulses from 30 ns to as long as seconds can be applied with pulse heights from 10 mV to 25 volts.

This circuit has been used successfully to measure majority carrier capture cross sections of the gold related acceptor level in silicon (Kalyanaraman and Kumar 1982), of interface states in MOS systems (Sen Gupta *et al* 1983), of deep levels in silicon due to alpha particle irradiation (Indusekhar *et al* 1984), and of iron related quenched-in defect in silicon (unpublished).

References

Indusekhar H, Sengupta D, Mohan Chandra M, Sreenath R N and Kumar V 1984 Investigation of alpha particle induced defects in n type silicon
3rd National Seminar on the Physics of Semiconductors and Devices, Bangalore, India

Janson L, Kumar V, Ledebo L-Å and Nideborn K 1981 A sensitive and inexpensive signal analyser for deep level studies
J. Phys. E: Sci. Instrum. **14** 464

Kalyanaraman V and Kumar V 1982 Properties of gold related acceptor level in silicon
Phys. Stat. Solidi (a) **70** 317

Lang D V 1974 Deep level transient spectroscopy: a new method to characterise traps in semiconductors
J. Appl. Phys. **45** 3023

Lang D V, Grimmeiss H G, Meijer E and Jaros M 1980 Complex nature of gold related deep levels in silicon
Phys. Rev. B **22** 3917

Sah C T, Forbes L, Rosier L L and Tasch Jr A F 1970 Thermal and optical emission and capture rates and cross sections of electrons and holes at imperfection centres in semiconductors from photo and dark junction current and capacitance experiments
Solid St. Electron. **13** 759

Sen Gupta D, Mohan Chandra M and Kumar V 1983 Direct measurement of interface state electron capture cross section in MOS system by DLTS technique
Phys. Stat. Solidi (a) **80** K209

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Determination of spin-polarisation for angle-resolved and energy-analysed secondary electrons

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Abstract. An absorption detector for electron-spin polarisation is combined with a compact energy analyser. The energy analyser has an energy-matching and transport lens at its entrance. This combination is used to measure the intensity, the intensity-asymmetry due to the modulation of primary beam polarisation, and the spin-polarisation of secondary electrons. Results are shown for secondary electrons from a Au(110) surface.

Studies of spin-dependent phenomena in electron spectroscopy require a detector for electron spin polarisation (ESP). So far the most widely used ESP analysers are based on high-energy Mott scattering (see review Kessler 1976). The spin-dependent diffraction of low-energy electrons from single-crystals has also been used to determine the ESP (Kirschner and Feder 1979). Recently, a simple and compact low-energy ESP detector has been realised; its operating principle is based on the spin-dependency in the electron absorption at a solid surface (Erbudak and Müller 1981, Celotta *et al* 1981). Whereas other ESP detectors are used in pulse-counting mode, with the absorption detector an electron current proportional to the ESP is measured without any ESP independent background. Therefore, the absorption detector is capable to measure ESP components varying periodically in time using analogue lock-in techniques. This additional utility can particularly be exploited if a spin-modulated primary electron beam is used from a GaAs photocathode. In this case, spin-exchange scattering between electrons, occurring in the production of secondary electrons in a solid, can readily be studied. Here, an apparatus based on these principles is described.

Figure 1 is a scale drawing of the apparatus showing its details. It consists of an energy-matching transport lens (TL), an energy analyser (EA), an electron deflector, and an absorption detector for determining the ESP. Spin-polarised primary electrons from a GaAs source hit the target. Electrons emitted from the target are accelerated by TL to a fixed pass energy, energy analysed by EA, and deflected by the deflector towards the absorption detector, where they are spin analysed.

The TL produces a virtual image in the plane of the target. Owing to the acceleration and the lateral magnification, the effective aperture of the detector assembly is increased and so is the detector current. S_1 is a 3 mm circular hole and restricts the filling factor to below 0.5. The first three elements of the TL provide a constant acceleration and image the emitting surface of the target into the field lens, see figure 2. The field lens, consisting of the third and fourth elements, operates in a

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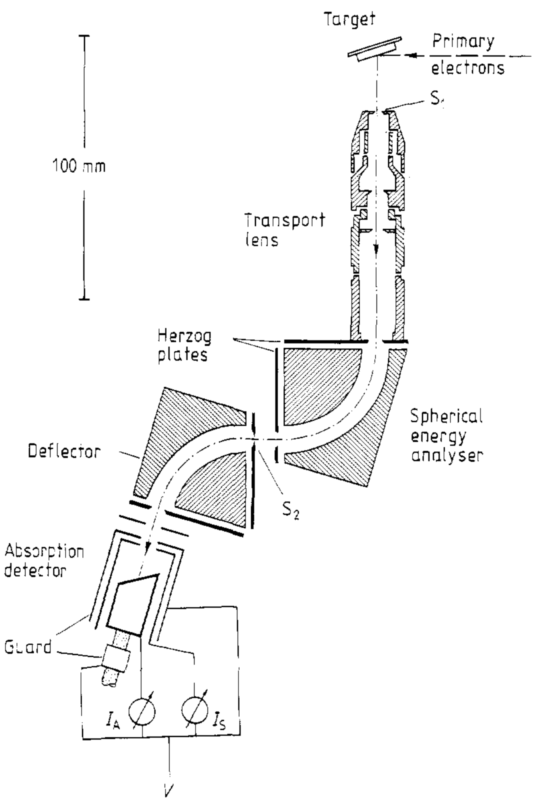

Figure 1. Scale drawing of the spin-polarisation detector consisting of a transport lens, an energy analyser, a deflector, and an absorption detector.

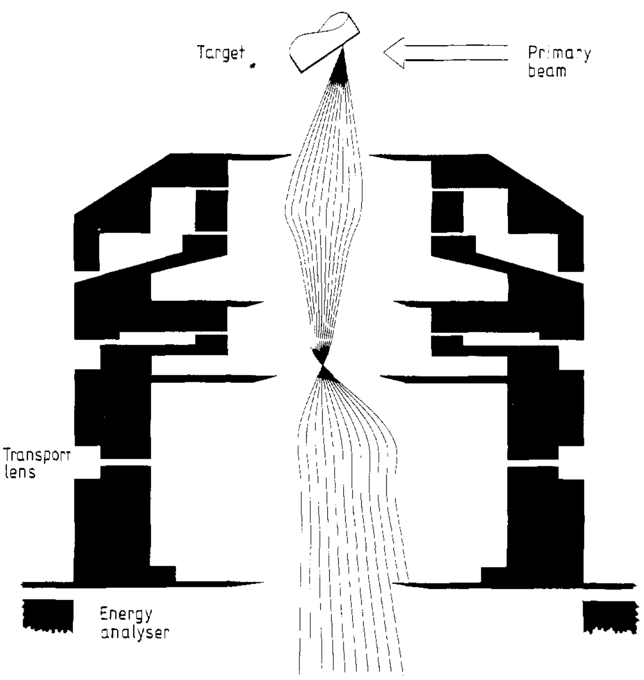

Figure 2. The transport lens and the trace of electrons calculated for secondaries leaving the target with a kinetic energy of 100 eV. Observe that the dimension perpendicular to the lens axis is expanded by a factor of 5 and the starting point of the electrons is the upper edge of the emitting surface of the target.

decelerating mode with a factor of 6 to 60 and provides the energy-matching (zoom effect). The fourth and fifth elements produce a constant acceleration by a factor of about 9 to get the constant pass-energy of the EA. This last lens produces a virtual image of the image in the field lens region; this virtual image lies then on the target plane. Figure 2 shows electron paths inside the TL. The lens geometry is designed using data for independent tube lenses (Harting and Read 1976) and the ray-tracing is performed for an idealised geometry neglecting the diaphragms in the field lens region, using available programs (Kisker 1982 and T Riesterer 1984, private communication). To be able to display several rays in figure 2, the dimension of the lens perpendicular to its axis is expanded by a factor of 5. Figure 2 illustrates paths of secondary electrons leaving the target with 100 eV. Their kinetic energy in several portions of TL is 100, 140, 825, 35, and 300 eV. According to the operation of TL, the latter two remain constant and the first three change proportional to the energy of electrons leaving the target as a spectrum is swept. TL produces a lateral magnification of 1.2 to 2.0 for $20 \leqslant E_p \leqslant 250$ eV. A constant magnification requires minute adjustments in the potential of the third lens.

The EA is a 90° spherical condenser working at constant pass-energy. For the sake of large transmission, S_2 is chosen so wide as to yield $\Delta E/E = 2\%$, which is determined by the FWHM of the elastically reflected electrons. The unwanted secondary electrons produced along the electron path are minimised by the deflector which works in tandem with the EA.

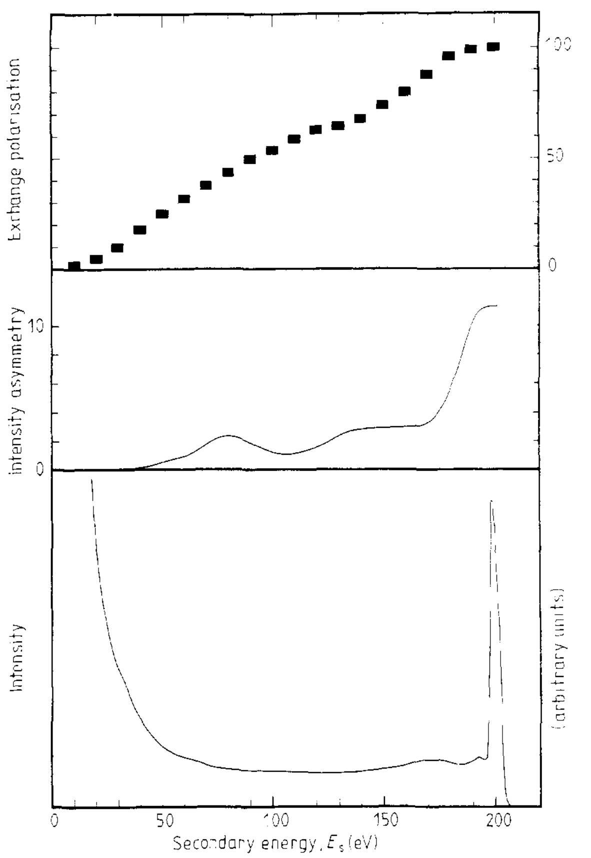

Figure 3. The intensity, bottom, intensity-asymmetry in %, middle, and electron spin polarisation in % due to primary electron spin-modulation, top, of secondary electrons emitted from a Au(110) surface. Primary energy (E_p) is 200 eV, scattering angle (θ) 90°, and the scattering plane coincides with the $(1\bar{1}0)$ mirror-plane of the crystal ($\varphi = 90°$).

The angle-resolved and energy-analysed electrons are decelerated to an energy E_0 and imaged onto the absorption detector by means of a three aperture asymmetric lens, see figure 1. The target for the absorption detector is a polycrystalline gold surface. E_0 is defined as the electron energy at which for unpolarised electrons the absorbed current I_A is zero. If the beam is spin-polarised there appears a finite current I_A at E_0 which is a measure for the ESP of that beam (Erbudak *et al* 1982). For our operating conditions, i.e., the angle of electron incidence is 30°, E_0 is typically 125 eV. The ESP of the incident beam is given by $P = C \cdot I_A/I_0$, where C is the polarisation sensitivity (about 200 in our case) and I_0 the electron current incident on the detector surface. The definition of E_0 and I_A guarantees that the current I_S backscattered from the absorber surface and then measured by the collector equals $I_0 + I_A$. Since C is quite large, i.e., I_A is about 0.5% of I_0 for a fully polarised beam, replacing I_0 by I_S produces a negligibly small error in the determination of ESP. Hence, I_S is measured at the collector and used in the above formula. The details of the operating principles of the absorption detector have been communicated earlier (Erbudak and Müller 1981). The electrical guards serve the purpose of eliminating the leakage currents over the insulators. In the detector geometry shown in figure 1, the detector is sensitive to the ESP component normal to the plane of the figure. If the detector is rotated by 90° about its axis coinciding with the direction of incident electrons, then the transverse component of the ESP lying in the plane of the figure becomes accessible. This versatility of the absorption detector has been applied to determine the two transversal components of the ESP occurring in LEED from Au(110) (Erbudak *et al* 1982).

In the following, this apparatus is employed to determine the ESP of secondary electrons emitted from a nonmagnetic surface, Au(110). The secondary electrons generally have an ESP which is a superposition of a 'static' value due to either spin–orbit coupling in case of large-Z-targets or magnetic exchange-interaction in magnetically ordered surfaces and the exchange-polarisation due to the transfer of spin of the primary electron onto a target electron and *vice versa*. With nonmagnetic targets the latter can only be observed if a polarised primary beam is used. The practical way to measure this effect is to use ESP-modulated primary electrons from a GaAs source and measure the ESP of the secondary electrons using the lock-in technique, which is just the suitable method to employ in conjunction with an absorbed current ESP detector. In this case, I_A is obtained as the in-phase signal of a lock-in detector. Using Burr-Brown OPAMP's OPA 104 CM with a feed-back resistor of $10^{11}\ \Omega$ as a preamplifier for a PAR 128 lock-in amplifier operating at a frequency of 4 Hz, we obtained a current detection limit of better than 0.5 fA(pp) with a time constant of $\tau = 100$ s. This means that in a measuring time of about 5 τ, the degree of ESP can be determined within 1% absolute accuracy if the beam intensity is about 5 pA.

Figure 3, bottom, shows the distribution of secondary electrons from a Au(110) surface. The primary energy is $E_p = 200$ eV and the scattering angle $\theta = 90°$. The spectrum in the middle illustrates the normalised change in the secondary current when the primary electrons are ESP-modulated; it is the so-called intensity-asymmetry. It is due to the spin–orbit coupling of electrons as they scatter at ion-cores. Also electrons other than the elastically reflected ones show a spin-asymmetry because the production of secondary electrons involves at least one ion-core interaction (Erbudak and Ravano 1982). On top, the exchange-polarisation of secondary electrons is plotted; this is the transfer of primary electron spin onto the secondaries. The data are normalised to the ESP of the primary beam, P_0. The spectrum shows that with increasing energy loss, secondary electrons' ESP gradually decreases. The true secondaries with very low kinetic energy have zero ESP. This is consistent with the fact that in the complicated cascade processes electrons lose their 'memory' and statistics dictate their distribution over states.

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References

Celotta R J, Pierce D T, Siegmann H C and Unguris J 1981 An electron spin polarization detector: Spin-dependent absorption of a polarized electron beam
Appl. Phys. Lett. **38** 577–9

Erbudak M and Müller N 1981 An efficient electron-spin-polarization analyzer
Appl. Phys. Lett. **38** 575

Erbudak M and Ravano G 1982 Spin polarization measurements of secondary electrons as a tool to study scattering mechanisms in a solid
Phys. Lett. A **91** 367–8

Erbudak M, Ravano G and Müller N 1982 Transversal polarization vector in LEED from Au(110)
Phys. Lett. A **90** 62–4

Harting E and Read F H 1976 *Electrostatic Lenses* (Amsterdam: Elsevier)

Kessler J 1976 *Polarized Electrons* (Berlin: Springer)

Kirschner J and Feder R 1979 Spin polarization in double diffraction of low-energy electrons from W(001): Experiment and theory
Phys. Rev. Lett. **42** 1008–11

Kisker E 1982 Simple method for accurate ray tracing in electrostatic lenses
Rev. Sci. Instrum. **53** 114–6