Fast Thermo-reflectance Bolometry

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We present a new approach to bolometry based on the measurement of the optical reflectivity change of a thin metal layer deposited on a transparent substrate. The reflectivity change of the metal layer results from the temperature rise due to absorption of energetic particles or X-rays. With this spectrally broadband and fast technique measurements of absolute energy fluxes are possible. Contact-less sensing makes this method well suited for measurements in an environment with a strong electro-magnetic noise.

The technique was applied to characterize a newly developed method for the generation of electron beams in dense gases. A very high efficiency for the e-beam generation, approaching 100%, was measured for the first time.

Introduction

The very invention of bolometry by S.P. Langley in 1881[1] has led to the first estimation of the so-called 'solar constant'. This fundamental quantity determines the incident power of Sun radiation per unit area of the Earth's surface and is frequently used in contemporary 'solar energetics'. Since then this technique found many applications in sensing radiation with wavelengths ranging from microwave through infrared and optical to soft X-rays [2,3].

There are three groups of bolometers, which differ by the temperature transducer types. The best known and most widely used 'resistive' (as was originally developed by Langley) and 'pyroelectric' bolometers make use of a temperature driven change of the electrical resistivity/dielectric constant of the sensor [3]. The 'infrared' bolometry utilizes the infrared radiation of the sensing element to measure its temperature [4].

These techniques have some known drawbacks. The resistive/pyroelectric bolometry relies on contact measurements of the electrical resistance/dielectric constant, thus it requires two electrical circuits: one to drive the bolometer and another one for readout. The presence of two cables acting as a ground/pickup loop causes problems due to additional electro-magnetic interference. Moreover, it is impossible to measure intense fluxes of charged particles with this technique, as an electric current associated with the flux of particles would result in false readings. The infrared bolometry suffers from its low sensitivity as it is necessary to measure the radiation flux produced by a minor ~10 K temperature change of the sensor with a small area (< 1 cm^2) located distantly (> 50 cm) from an infrared detector.

The new thermo-reflectance bolometry proposed by us does not have these drawbacks. It uses the change in the optical reflectance of a sensor element due to a

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temperature change. The physical property of materials to change their reflectance with temperature is well known and has a wide range of applications in studies of band structures of semiconductors [5] and estimations of thermo-physical constants of thin surface films [6]. However as far as we know it has never been used for bolometry.

Bolometer

We prepare our bolometers by evaporating thin metallic films (approximately 1 μm thick) onto transparent substrates with low thermal conductivity such as Pyrex or Quartz. X-rays or energetic particles like for example electrons reach the metal film through an opening in a ring (Fig.1.). This ring serves both as a holder for the sensor and as its ground connector. The energetic radiation is absorbed in the bolometer film. The resulting energy absorption ends up heating the bolometer film. The rate of this process is determined by the specific heat of the material and the heat diffusion into the substrate. The metal/substrate interface is illuminated by an external light source. The temperature change of the film alters the optical reflectance at the interface thus modulating the intensity of the reflected light. An appropriate fast photo detector measures the intensity of the reflected light. The interface temperature as well as incident power and/or energy are thus determined.

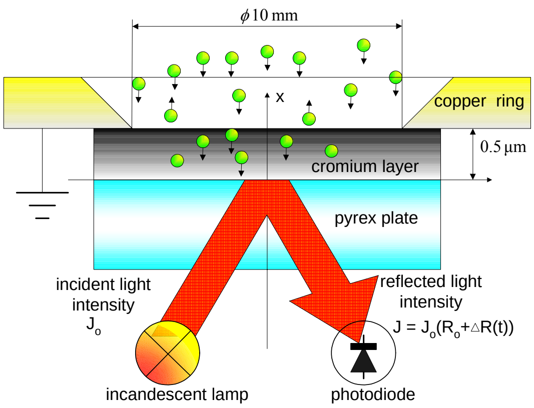

Fig.1. Sketch of thermo reflectance bolometer

While designing the bolometer one should find a compromise between its sensitivity and opacity for the radiation to be measured. We use thin chromium films for our bolometers. There are several reasons for this choice.

The thermo reflectance spectrum of chromium has a wide peak at the wavelength of ~ 1μm [7]. This wavelength region ideally matches with the maximal response of most Si photodiodes. Also, an incandescent halogen lamp is a convenient illumination source in this spectral range.

Chromium is a sufficiently dense material, thus electrons with an energy of ~ 20 keV can be stopped in films with sub-micron thicknesses. Meanwhile, the backscattering energy coefficient of chromium does not exceed ~ 0.2 thus corrections due to electron backscattering are small compared to more heavy materials (Cu, Ag, Au et.c.).

Chromium is often used in thin-film coatings, especially as an adhesion layer for other metal coatings. Thus if one wants to increase the opacity of the bolometer for radiation of higher energy, it can be easily done by depositing an extra layer of the material that is more dense than chromium on top of the original layer.

A comprehensive theoretical model of thermo-reflectance bolometer was developed. The relationship between the absorbed power P(t) and the observed electrical signal is determined by a set of equations:

$$P(t) = c_m \rho_m h \frac{d}{dt} T(t) + \sqrt{\frac{\lambda_g c_g \rho_g}{\pi}} \int_0^t d\xi \frac{d}{d\xi} T(\xi) \frac{1}{\sqrt{t-\xi}}, \quad (1)$$

$$\tau \frac{d}{dt} U(t) + U(t) = \frac{1}{R} \frac{dR}{dT} T(t)$$

Here T(t) is the change of the interface temperature, U(t) is the photodiode response, R is the interfacial reflectivity, c_m, ρ_m, c_g, ρ_g are the specific heat capacity and the density of the metal film and substrate correspondingly, λ_g is the thermal conductivity of the substrate, τ is the response time of the photodiode. One sees that the use of substrates with a small λ_g is preferable. In opposite case the power loss due to the heat diffusion into substrate should be taken into account.

Calibration procedure and the proof of principle experiments.

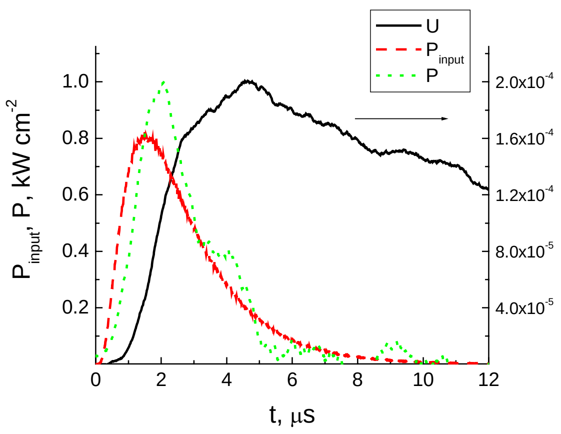

Fig.2. Pulses of the thermo reflectance signal U, input power P_{input} and calculated power P

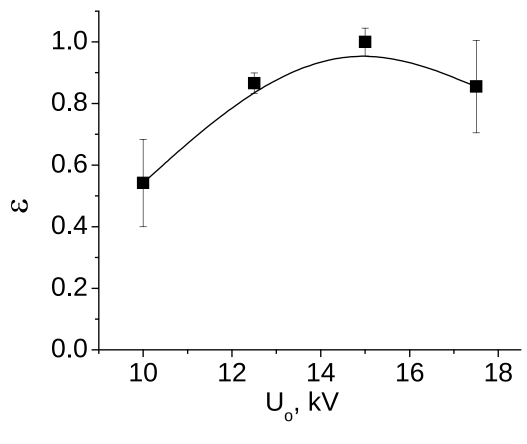

Fig.3. Energy efficiency of the e-beam generator. The working gas was He at 10 mbar

To calibrate the device in absolute units an electrical pulse of known power and energy was sent through the bolometer and the resulting thermoreflectance signal was measured. This was done by discharging a capacitor through the bolometer film. In this way, all the constants from the equations (1) could be determined. The results of this calibration procedure are shown in Fig.2. Signals of the input power P_{input}, photodiode thermo reflectance signal U and power P, derived with the use of (1) are presented. A bolometer with a 0.5 µm thick chromium film on a Pyrex substrate was used. The response time of the photodiode used in this experiment was ~ 400 ns. It is clearly seen that, besides energy measurements, this simple and robust technique allows also for power measurements provided the photodiode circuitry has an adequate temporal resolution.

The thermo-reflectance bolometer was successfully used to measure the energy of an electron beam. Such beam with a current density of ~ 60 A/cm^2 and electron energy of ~10-20 keV was produced by an open dielectric barrier discharge generator directly in a working gas at pressure up to ~ 100 mbar [8]. The main problem in the evaluation of the energy efficiency of the generator was the necessity to separate the power inputs into the gas from the electron beam and from the beam generating discharge. A non-contact measurement of the incident input power with sub-microsecond time resolution was required. Other known techniques failed in these harsh experimental conditions, while the thermo-reflectance bolometer demonstrated the desired performance. The dependence of the energy efficiency on the charging voltage of the generator U_0 is shown in Fig.3. The extremely high efficiency of a dielectric barrier discharge based generator is clearly seen. It should be noted that the energy efficiency of an open discharge is measured for the first time. It became possible only due to implementation of the new thermo-reflectance bolometry.

Conclusion

Summarizing, the advantages of thermo-reflectance bolometry are as follows:

- Broadband and robust technique that measures absolute fluencies of energetic particles and/or radiation ranging from microwaves to soft X-rays.
- Non-contact sensing avoids problems of electromagnetic interference.
- The method is fast (response time up to ~ 10 ns).
- The signal to noise ratio is determined by the photodiode shot noise. This ratio can be improved by using a high power illuminating source. An incandescent lamp is ideally suited for this purpose.

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