Optimization of an electrometer on noise and linearity

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(Received September 30 1998; accepted January 11 1999)

Electrometers are the only electrons and charged particle detector traceable to the SI system. An electrometer was optimized on the noise and linearity to obtain standard Auger electron spectra. We have found the product of *I* and *R* has the critical value of *2kT/e* (about 50mV at room temperature) relating to the noise characteristic, where *I* is a measuring current and *R* is a detecting resistance. We found that the linearity degraded for the values of *IR* higher than 10 V. The *IR* values of 0.1 through 10V are the optimum.

Key words : electrometer, optimization, noise, linearity

1. Introduction

We have developed a novel cylindrical mirror analyzer (CMA) for an Auger electron spectroscopy (AES) traceable to the SI system [1]. The SI is an abbreviation of the " Le Syste`me International d' Unit`es". This CMA detects the Auger electrons with a Faraday-cup connected to an electrometer which is the only electron (charged particle) detector traceable to the SI system. For the accurate measurements, the noise and linearity characteristics are the most significant factors, particularly in the high sensitive experiments.

In this study, we investigated; 1. both the theoretical noises of the Johnson noise [2,3] (thermal noise inherent to the resistance) and the Schottky noise [4] (particle noise inherent to the signal current), 2. the noise of the electrometer obtained experimentally, and 3. the experimental linearity and the range of linearity. By considering these three factors, we optimized the electrometer for the practical use.

2. Experimental

An electrometer of Keithley model 642LN (the lowest noise version), and the discharge type pen recorder of HIOKI 8201 Micro Hi Corder have been employed in noise experiment. The elastically back scattered primary electron spectrum from Si (111), 0 through 10 pA, was measured with our CMA [1]. As the CMA system offered the lowest input capacitance, then thus it showed nearly the inherent noise characteristic of the electrometer. A schematic electrometer is shown in Fig.1. In noise experiment we chose $R=10^{12}\,\Omega$, which is the most sensitive range and the time constant was adjusted to the 1.5sec. The direct output of the Keithly model 642LN was connected to the recorder through an ac-coupling of a time constant of 1.2sec.

Another electrometer of a Keithley model 610C (capable of 100V output) and a picoampere source of calibrated Keithley model 261 have been employed in a linearity experiment. We chose the full scale ampere ranges of the electrometer from 10^{-6} A to 10^{-12} A. Although the model 610C has not provided a range resistor of $10^{12}\,\Omega$ for the 10^{-12} A measurement, then we replaced the range resistor of 10KΩ by a $10^{12}\,\Omega$. By varying the dial of the picoampere source we obtained the output voltage from 0.001V to 100V, which is the voltage applied to the detecting resistors.

All instruments were warmed up at least two hours and kept the temperature about 27℃ [5].

3. Results and discussion

Fig.2 shows the obtained noise characteristics for the $10^{12}\,\Omega$ of the range of the detecting resistor of the model 642LN. The noise increased for the higher output voltages, i.e., the input currents. It seems that the noise increases as a square root of the signal current from a certain corner ~; around 0.1~ 0.5 V. i.e, 10^{-13} ~ 5×10^{-13} A of the output.

There are three kinds of noises; (1)thermal (Johnson or Nyquist) noise inherent in the resistance *R* (ohms), (2)particle (Schottky or shot) noise which is a statistical fluctuation of the signal current (flow of the charged particles), and (3) the additional noise.

The thermal noise in the source resistance gives the fundamental limit to the measurement, irrespective of the signal current. In any resistance, thermal energy produces motion of the charged particles. This charge movement results in noise which is often called thermal or Johnson noise and is given by :

$$e_J = \sqrt{4kTRB}\ \mathbf{Vrms} \qquad (1)$$

where *k* is 1.38×10^{-23} J/K (Boltzmann constant), *T*(K) is temperature, *R*(Ω) is resistance being used in the detecting resistor and B(Hz) is the bandwidth. The noise bandwidth is $\pi/2$ times the -3dB frequency limit of the circuitry (f_{-3dB}),

$$B=\pi(f_{-3dB})/2$$
$$=\pi/4\pi RC$$
$$=1/4\tau \qquad (2)$$

where R is the resistance of the detecting resistor and C is the effective capacitances shunting the resistance which includes the effective input capacitance (C_{in}; input capacitance, cable capacitance,.etc) [7]. We get $B=1/4\tau \approx 0.17$ Hz as τ being 1.5 s.

The Johnson noise developed in the resistor $R(\Omega)$ is, $e_J = \sqrt{4kTRB}$ **Vrms**. Statistical considerations show that peak-to-peak noise will be about five times the rms noise for about 99% of the time by neglecting the most highest and lowest peaks, therefore, the rms is commonly multiplied by five to convert it to peak-to-peak noise [6]. At room temperature (300K), the above equation (1) becomes, $E_{p\text{-}p}=6.4\times10^{-10}\sqrt{RB}$. If the input current is I and the output voltage is IR, then $S/N= IR/\sqrt{4kTRB} \propto \sqrt{R}$, which means the larger the resistance the higher the signal to noise ratio will be.

The Schottky noise is the fluctuation of the signal current. Similarly the Schottky noise can be shown as :

$$i_s= \sqrt{2eIB}\ \text{Arms}, \qquad (3)$$

where $e = 1.60\times10^{-19}$C, I(A) is the signal current and B(Hz) is the bandwidth. If the input current is I, then $S/N=I/\sqrt{2eIB} \propto \sqrt{I}$, which means the higher the current the higher the signal to noise ratio will be. The Schottky current noise can be transformed to that of the voltage by the detecting resistor R as $e_s=i_s\times R$ at the output of the electrometer.

The theoretical curves of Johnson noise and Schottky noise cross at the critical point, (Fig.2), which can be obtained by equating $\sqrt{4kTRB}=R\times\sqrt{2eIB}$, from which we get $I\times R=2kT/e$=52mV at T=300K.

Fig.2 shows the theoretical and experimental output voltage vs noise current characteristic. For the higher voltage above the critical point the noise mainly consists of the Schottky noise which increases as a square root of the signal. While that below this point, the noise will mainly consist of Johnson noise which practically remains constant and does not depend upon the signal. This means that the signal will be buried under the Johnson noise in this small signal range .

The experimentally obtained noise characteristics, however, show about 4 times worse feature than those of theoretical prediction. This can be due to the additional noises arising from many causes which are too complex to analyze. Though the experiment would reflect the theoretical critical property. According to these results and consideration, it should be better to use an electrometer above 0.1V of the output for a practical use.

Fig.3 show the relationship between the error in the linearity and the output voltages. The linearity for the whole detecting resistor was better than 1% when the output voltages were below 10V. However, for the output voltages above 10V, the linearity varies more remarkably for the higher resistors. When the output voltage is 10V the relative errors were -0.43%($10^{12}\Omega$), -0.27%($10^{11}\Omega$), -0.02 %($10^{10}\Omega$), -0.01%($10^{9}\Omega$) and when the output voltage was 20V, the relative errors were -1.1%($10^{12}\Omega$), -0.75%($10^{11}\Omega$), -0.08%($10^{10}\Omega$),-0.41%($10^{9}\Omega$) and when the output voltage was 100V the relative errors were -6.9%($10^{12}\Omega$), -6.2% ($10^{11}\Omega$), -2.7%($10^{10}\Omega$), -2.4%($10^{9}\Omega$). While the resistors of 10^{6}-10^{8} Ω showed no remarkable changes. From the results it is clear that the error in the linearity would appear for the higher resistors when the output voltage is above 10V. These linearity errors would consist in the resistive materials. We should use and design an electrometer below 10V of the output voltage.

4. Conclusions

From the results presented in this study it is obvious that the lower the output voltage the lower the signal to noise ratio can be, though the error in the linearity would appear for the higher detecting resistor when the output voltage is above 10 volts. Therefore it is advisable that the electrometer should be designed or used for an output voltage in the range of 0.1V through 10 V.

5. Acknowledgements

The authors would like to thank Mr.H. Kuruobe and Mr.H.Yamamoto for their help in preparing the graphs.

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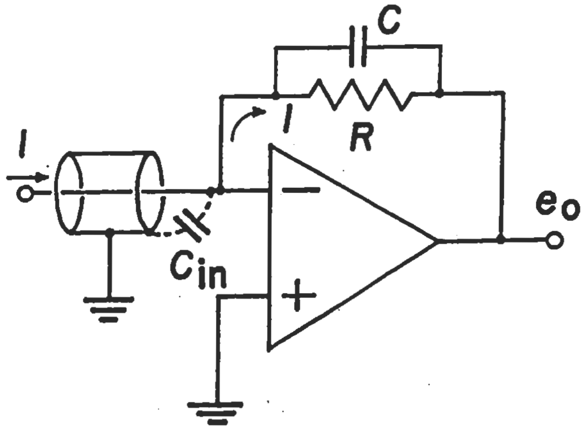

Fig.1. A schematic drawing of an electrometer.

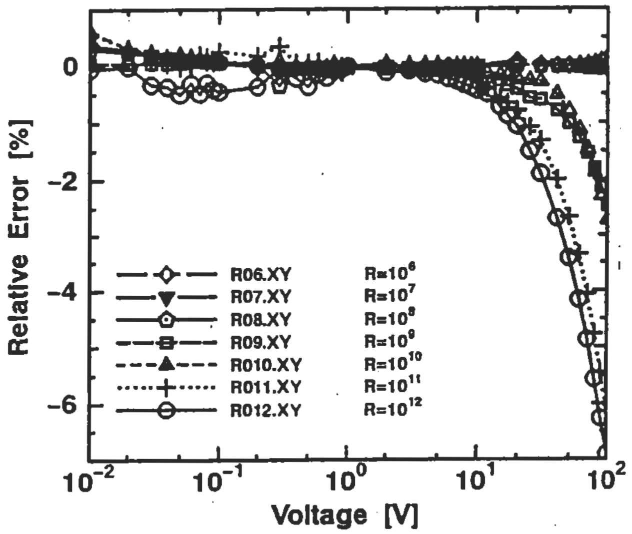

Fig.3. The linearity characteristic with resistors and output voltages.

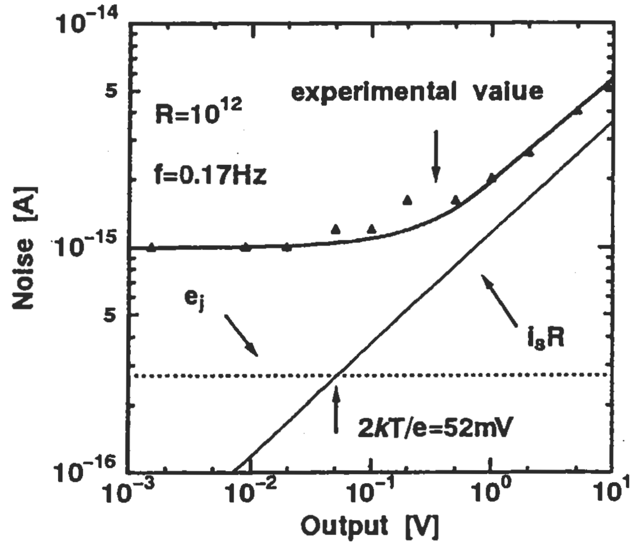

Fig.2. Noise characteristic of the resistor for the range of 10^{12}.