REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 084702 (2017)

Electrometer with sub-attoampere current load

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(Received 5 May 2017; accepted 31 July 2017; published online 18 August 2017)

By cooling a conventional junction field-effect transistor below 150 K, a simple and versatile electrometer with extremely high impedance can be realized. At operating condition, the leakage current to the gate amounts to a few hundredths of an attoampere. The electrometer can be used from DC up to a frequency of 10 kHz. Without reduction of the bandwidth, a sensitivity of a few μV is obtained. Working at low frequencies, currents as low as a few attoamperes can be detected. If the input voltage is out of the operational range, the forward current or the Zener current of the gate junction protects the transistor against destructive charging. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4998979]

Ideally the measurement of voltages should be performed without loading the source by a current. At high voltages, purely static measurements can be easily performed, e.g., by a gold-leaf electrometer.[1] However, for the range of volts or even lower, the sensitivity is insufficient and other mostly electronic techniques are applied incurring parasitic currents that are in the range of 10^{-15} A for state of the art electrometers that are commercially available.

Very low DC current loads have been achieved by "vibrating-reed electrometers" transforming a static charge into an AC current by mechanical modulation of a capacitor.[2–6] However, these techniques require sophisticated experimental setups, using micromechanics, a special rotor, etc. Due to the principle of the operation, the detection is limited to more or less static signals since the information is recovered by averaging over several periods of the modulation.

Another approach to achieve ultimate charge sensitivity is the "Coulomb blockade electrometer" or single electron transistor. In order to operate the device in the single electron tunneling regime, the thermal energy kT has to be lower than the Coulomb energy $e^2/2C$, with C equal to the sum of the junction capacities. In practice, the criterion is fulfilled for temperatures in the mK range.[7–9]

It is well known that the impedance of a junction field-effect transistor (JFET) as well as the noise performance increases upon cooling. Cryogenic cooling of a JFET input stage is applied, e.g., for semiconductor detectors for infrared or X-ray radiation.[10,11] Recently, a scheme for a low noise and low bias transimpedance amplifier for sub-picoampere currents based on conventional electronics was presented,[12] achieving a bias of only 100 aA. Michel *et al.*[13] proposed a high bandwidth, low noise transimpedance amplifier using a FET input stage at cryogenic temperature.

Here, we show that an excellent performance, i.e., almost vanishing input offset current, may be achieved by a very simple and versatile setup, using a commercial JFET that is cooled far below the range specified by the manufacturer.[14] Lindström and Holmer[15] have shown that the leakage gate current of a typical JFET is reduced by a factor of 25 going from 25 °C to −20 °C. The leakage current is equivalent to the temperature dependent reverse current in the depleted p^+n junction at the gate contact. Besides the diffusion of charge carriers into the depletion region, the thermal generation of electron-hole pairs contributes to the current under reverse bias.

As will be discussed in more detail,[16] the leakage current in p^+n junctions of indirect semiconductors with band gap energies above 1 eV and for temperatures below 300 K is completely dominated by the generation process. These conditions are met in the present study since the used JFET (BF545) is fabricated from silicon with an indirect band gap energy above 1.12 eV. As a consequence, the generation process can be modeled by the Shockley-Read-Hall statistics[17,18] leading to the reverse current density

$$j_r \approx \frac{e_0 W}{\tau} n_i \propto \exp\left(-\frac{E_g}{2k_B T}\right),$$

where W is the depletion layer width, τ is the generation lifetime, and n_i is the intrinsic charge carrier concentration. The prefactors are typically slowly varying with T. Therefore, the temperature variation of the reverse current is governed by n_i, i.e., it exhibits an Arrhenius type dependence with an activation energy equal to half of the band gap.

Hence, by cooling below 150 K, the leakage current can be reduced by about 5-6 orders of magnitude. Using appropriate insulation, the remaining leakage current at $T < 150$ K is in the order of 10^{-20} A, thus enabling us to build an almost "ideal" electrometer.

Prior to the further measurements, the input capacity of the FET was measured at 80 K. A sinusoidal signal of 1 kHz was applied to the gate and the displacement current to source and drain was evaluated. The two latter were shorted. The capacity varies between 3.9 pF at $V_{gate} = -3$ V and 5 pF at $V_{gate} = 0$ V. The values are close to the specifications at room temperature.

Figure 1 shows the scheme of the electrometer using an open gate circuit. Only the input stage with a conventional n-channel junction FET (BF545 B) is cooled to a temperature of 80 K. The drain current is converted to a voltage by a transimpedance amplifier with $-U_{out}/I_{drain} = R_2 = 10$ kΩ maintaining a constant source drain voltage, thereby reducing a capacitive cross talk to the gate electrode. The drain

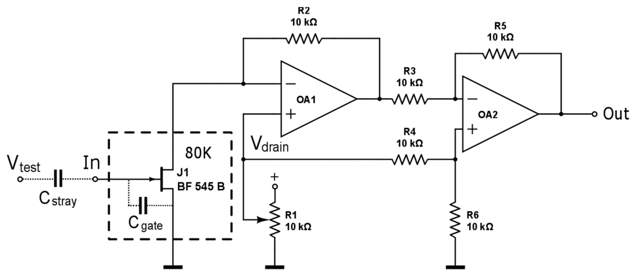

FIG. 1. Schematic representation of the electric circuit used for the experiment.

voltage is adjusted by the potentiometer R_1. The second operational amplifier provides a signal with reference to ground by differential amplification of the output of the transimpedance amplifier and the drain voltage.

Figure 2 displays the drain current I_{Drain} as a function of gate voltage V_{Gate} for a source drain voltage of 3 V at 298 K and at 80 K. At low temperatures, the drain current is reduced compared with room temperature. The curve shifts towards the positive gate voltage, but it remains in a useful range for electronic applications. The same transistor was used for the results presented in the paper. It was operated typically at $V_{Gate} = -1.9$ V. From the slope, a transconductance of 1.56 mA/V can be determined. Using the transimpedance of the circuit of Fig. 1 yields a ratio of $U_{Out}/V_{Gate} = 15.6$. In the following, the latter has been used to calculate the gate voltage or input voltage based on the measured output voltage. To avoid joule heating of the transistor, the drain current was limited to about 1 mA.

Different modes of operation of the electrometer have been tested. Since, at 80 K the leakage current is completely negligible, the JFET can be operated at the open gate, i.e., the input of the JFET is not connected to any external circuit.

To demonstrate the performance of such an electrometer, the signal V_{test} is applied to the gate only by the capacitive cross talk from an adjacent electrode (indicated by the dotted line and C_{stray} in Fig. 1), thereby avoiding any DC current to the gate. Even the static voltage of the gate may be adjusted by a static voltage of an electrode nearby.

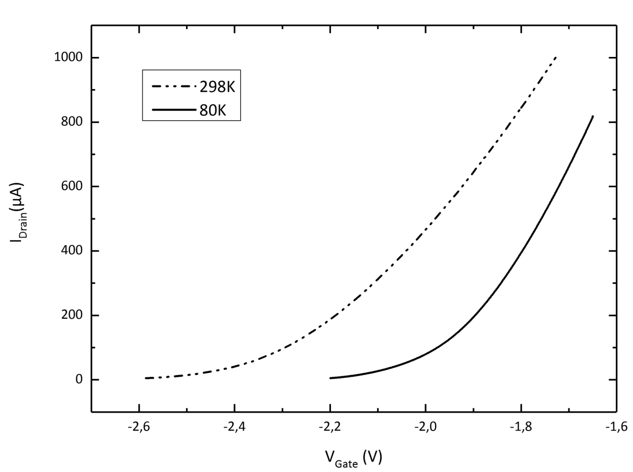

FIG. 2. Drain current vs. gate voltage for a BF545 B JFET at 298 K and 80 K.

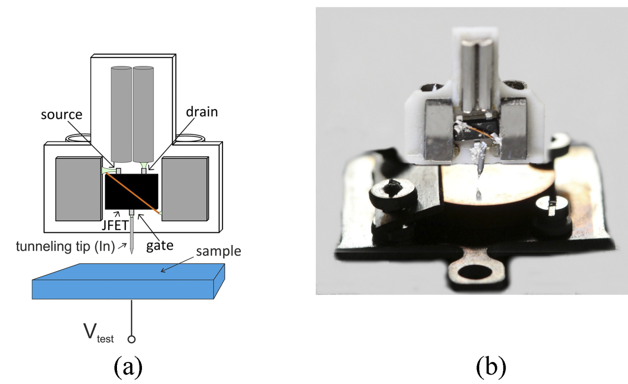

FIG. 3. (a) Schematic drawing of the experimental arrangement and (b) photocomposition of the JFET sensor for application in a low temperature scanning tunneling microscope.

Figure 3 displays the experimental setup that is designed for a low temperature scanning probe microscope operated in an ultra-high vacuum setup. The tip of a scanning tunneling microscope is connected to the gate of the JFET. The sample which is kept at a distance of a few µm may be used as an electrode for capacitive input coupling. The stray capacitance, C_{stray}, between the tip and sample and the gate capacitance, C_{gate}, of the JFET act as a voltage divider with a ratio of $C_{gap}/(C_{gate} + C_{gap})$. In the experiment, the latter varies around 0.03 depending on the shape of the tip and the distance to the sample. As pointed out above, the gate capacity including the tip was measured at the operating condition at a gate source voltage of −1.9 V and T = 80 K; it amounts to 4.1 pF.

Figure 4 displays the unfiltered signal at the output if a rectangular input signal of 60 μV_{pp} is applied at the gate (+/− 1 mV at the adjacent electrode, i.e., the sample). The gate source voltage was adjusted to −1.9 V. The resolution can be estimated to about 10 μV at a bandwidth of about 10 kHz. So far no specific effort was made to improve the frequency response, but preliminary tests reveal that a bandwidth of 100 kHz can be easily achieved.

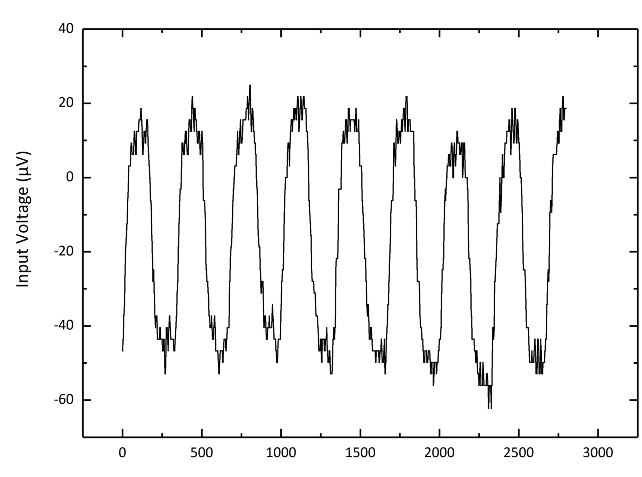

FIG. 4. Output signal for a rectangular input signal of 60 μV_{pp} at the gate. For clarity, the output signal of the amplifier was divided by the combined gain of the JFET, the transimpedance, and the differential amplifier. Hence, the signal is scaled to the input voltage.

Knowing the capacity, the sensitivity for application as a charge amplifier can be estimated to be about $\Delta q = C\Delta U = 4.1\,\text{pF}\,10\,\mu\text{V} = 4.1 \times 10^{-17}\,\text{C} \cong 250\,e$ for a bandwidth of about 10 kHz. ΔU is the voltage resolution as estimated above.

By low pass filtering, the resolution may be further increased. Figure 5 shows the results for a rectangular current signal alternating between +0.75 aA and −0.75 aA, which was induced by a sawtooth signal V_{test} of +/− 3 mV and 0.0005 Hz of the electrode (sample) nearby. This corresponds to a charging rate of around 5 *e*/s. The signal can be unambiguously detected. However, a long term drift of about 7×10^{-20} A can be recognized. Figure 5(a) displays directly the output of the circuit, and Fig. 5(b) shows the input current calculated according to $I = C\frac{dU}{dt}$ using C = 4.1 pF. The differentiation was performed using a sliding window with a width of 20 s. If the system is allowed to settle for some time, a drift or leakage current of 4×10^{-20} A is found for a time of three days.

In the light of application, the electronic noise of the JFET is crucial. As shown in the spectral density of noise in Fig. 6, the input voltage noise is rather constant at somewhat less than $100\frac{\text{nV}_{rms}}{\sqrt{\text{Hz}}}$ for frequencies above 1 kHz; at low frequencies 1/f noise becomes dominant.

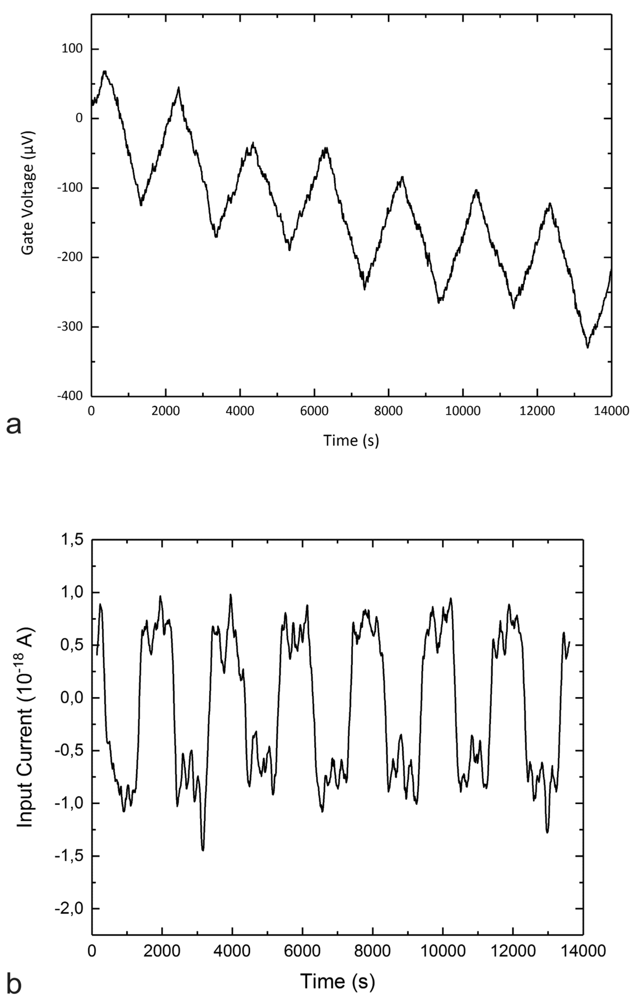

FIG. 5. Output signal for a rectangular input current alternating between +0.75 aA and −0.75 aA. (a) displays the output of the electronic circuit; the signal is scaled to the input voltage. (b) shows the calculated input current using a window of 20 s.

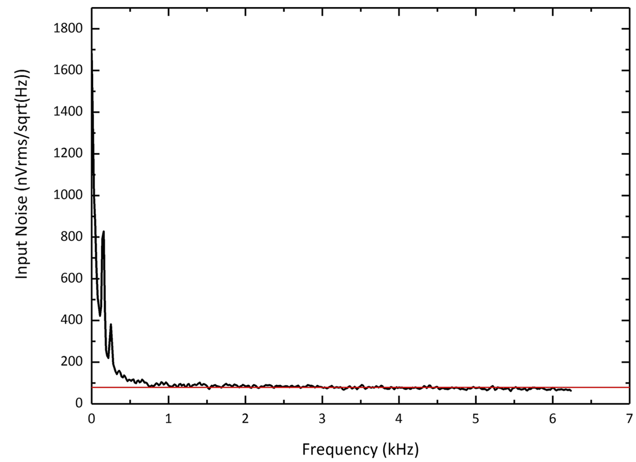

FIG. 6. Voltage noise of a BF545 B JFET at 80 K. The signal is scaled to the input voltage.

In a preliminary experiment, scanning tunneling microscopy was performed by applying a superposition of a DC voltage defining the working point and an AC voltage to the sample. The AC component of the measured signal may be used for adjusting the tip sample distance.[19]

To demonstrate the performance, in especially the long term stability, of the electrometer, changes of the work function of the electrodes due to adsorbates have been studied. Prior to the measurement, a Cu(111) sample was cleaned by ion bombardment and thermal annealing. Figure 7 displays the signal if the sample and the tip facing the sample are exposed to CO, by applying a partial pressure of $p = 5 \times 10^{-7}$ mbar outside of the cooled experimental setup. After 2500 s, the voltage at the sample was readjusted from −1.90 V to −1.79 V to restore the starting value of the gate voltage. This corresponds to a work function decrease of 110 meV by CO adsorption. The value is smaller than the reported 270 meV observed for a densely packed CO layer on Cu(111) at 104 K.[20] In addition, the typical overshoot in the submonolayer range is not detected in Fig. 7. This discrepancy may be due to a potential CO coverage on the tip. Still, Fig. 7 demonstrates a proof of principle that the setup allows static measurements of local electrical potentials in the μV range.

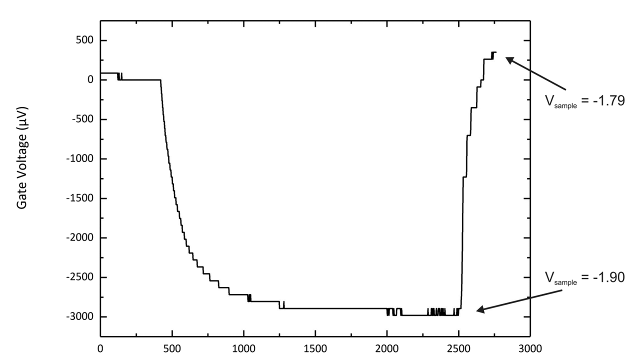

FIG. 7. Change of the gate voltage if CO is adsorbed on the Cu(111) sample (and at the tip) at 80 K. The vertical scale displays the difference to the gate voltage at t = 0. At t = 2500 s, the sample voltage was changed from −1.90 V to −1.79 V to restore the gate voltage without CO.

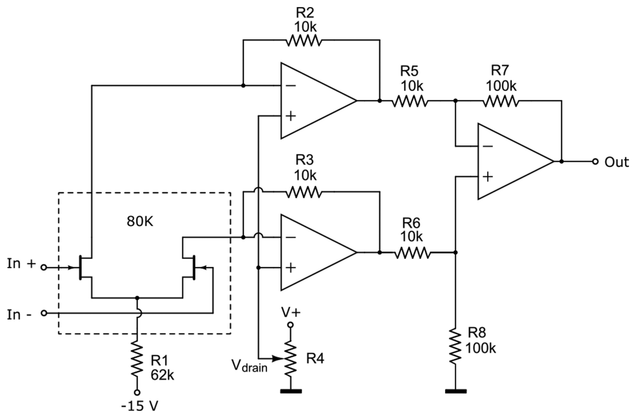

FIG. 8. Proposed design for a differential input electrometer using two JFETs at low temperatures.

The electric scheme presented in Fig. 1 was used to obtain the results presented in Figs. 4–7. However, for practical application, the large input offset of −2 to −1 V can be cumbersome. The problem may be circumvented by a differential JFET input stage using a pair of JFETs cooled to 80 K. Figure 8 shows a possible scheme. The drain voltage is adjusted by R4, e.g., to 3 V. For the chosen parameters, the drain current of the transistors will settle at about 100 μA, if the input is close to ground. If the resistors R1, R2, and R3 are included in the cooling stage, their thermal noise can be reduced. However, it should be noted that the noise will be dominated by the JFETs and it is expected to increase by a factor of $\sqrt{2}$ as compared to the single ended scheme presented in Fig. 1.

In summary, our findings reveal that by cooling a conventional n-channel junction FET, an almost ideal electrometer can be built, which offers many advantages in practical application because of its simplicity and robustness. The current load given by the gate leakage current is in the order of a few 10^{-20} A. At a bandwidth of 10 kHz, a sensitivity of about 10 μV or 250 elementary charges is obtained. For a reduced bandwidth, attoampere resolution could be demonstrated. Despite the high electric sensitivity, the JFET is not prone to harmful electric charging. Outside of the working range, the input becomes conductive and withstands input currents of 50 μA without damage.

Due to the ultimate low current load, it may be applied for many different experiments in physics, chemistry, or biology. For example, in the field of scanning probe microscopy, it will enable potentiometry on delicate structures of very high impedance.

This work was supported by the Deutsche Forschungsgemeinschaft through No. SFB1242 "Non-equilibrium dynamics of condensed matter in the time domain."

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