

Temperature dependent electrical characteristics of a junction field effect transistor for cryogenic sub-attoampere charge detection

Cite as: AIP Advances 9, 025104 (2019); doi: 10.1063/1.5077039

Submitted: 24 October 2018 • Accepted: 30 January 2019 •

Published Online: 11 February 2019



View Online



Export Citation



CrossMark

Anahita Kavangary, Paul Graf, Hüseyin Azazoglu, Meike Flebbe, Kornelia Huba, Hermann Nienhaus,^{a)} and Rolf Möller

AFFILIATIONS

Faculty of Physics, University of Duisburg-Essen and Center for Nanointegration Duisburg-Essen (CENIDE), Lotharstr.1, 47048 Duisburg, Germany

^{a)}Electronic mail: hermann.nienhaus@uni-due.de

ABSTRACT

Junction field effect transistors (JFET) at cryogenic temperatures can be employed as almost perfect charge detectors with leakage currents of less than 1 aA. The electrical input and output characteristics of the commercial n-channel silicon JFET BF545B is studied as a function of temperature in the range between 30 and 300 K. As long as the charge carrier concentration is constant an increasing drain current is observed for reduced temperatures and low gate voltages. Using a constant mobility model for the device this behaviour can be explained with the higher electron mobility in the source-drain channel. The mobility is found to increase with T^{-1} at lower temperatures which corresponds to a dopant concentration of $7 \cdot 10^{16} / \text{cm}^3$. For larger negative gate voltages a source-drain voltage is found at which the drain current is almost temperature independent. As soon as the charge carriers freeze out the input characteristics changes significantly due to the exponential decrease of the carrier concentration. The effective reduction of the gate leakage current is crucial for ultimate sensitive charge detection. Hence, the current is measured through the entire temperature range in an open gate configuration. The leakage current decreases exponentially with lower temperatures across more than six orders of magnitude and reaches values of 10^{-20} A below 160 K. It is exclusively due to the generation of electron-hole pairs in the depletion layer since the data are in full agreement with the Shockley-Read-Hall model of the generation current.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.5077039>

I. INTRODUCTION

Ultimate charge detection requires electrometers with an extremely large input impedance. This is typically achieved by use of field effect transistors (FET) on the input stage which allows to probe charge and voltage with current loads of ≤ 1 fA in commercially available devices. This is still insufficient for measurements of a few to hundreds of elementary charges. Cooling of the FET can improve the performance as it lowers the noise level and increases the input impedance. Operation of electronic devices at low temperatures has been a key technology for decades,¹ e.g., in space research, for satellites and

charge sensitive particle or radiation detection. The field came to birth with the pioneering work of Gerritsen and van den Burg² in 1951.

In case of FETs, the gate is either isolated from the source-drain channel by an insulating layer (MISFET, MOSFET) or by a reverse biased pn -junction (JFET).³ While a typical MISFETs still works at liquid helium temperature the JFET stops operation below 50 K due to freezing-out of the charge carriers. However, the JFET exhibits the advantages of a lower noise level and a larger robustness to uncontrolled electrostatic discharges.⁴ Thereby, JFETs are the preferred input transistors in charge sensitive preamplifiers or impedance

converters. The device characteristics at low temperatures have been studied widely in basic research⁴⁻¹¹ or, e.g., for Ge-based particle detectors,¹² for infrared detection¹³ or for low-noise electrometers.^{14,15}

The ultimate input impedance of the JFET is determined by the leakage current which is the current through the reverse-biased pn -junction of the gate contact. It decreases exponentially with lower temperature as already shown in an early study in the temperature range between 260 and 360 K.¹⁴ The authors measured in one of their devices a leakage current of 10^{-14} A at 260 K. Recently, we could demonstrate that this value can be reduced by orders of magnitude using the commercial JFET BF545B at 80 K in an ultrahigh vacuum (UHV) environment with almost perfect electrical and thermal isolation.¹⁶ With open gate, i.e., with no connection of the gate to any outer terminal we observe currents of a few 10^{-20} A. Accordingly, the present study draws the attention on the temperature dependence of the DC input and output characteristics and of the leakage current. Using standard models, the data allow the quantitative deduction of device parameters and its material properties.

II. EXPERIMENTAL METHODS

In the experiments the commercially available n -channel Si JFET BF545B in a plastic surface mounted package (SOT23) is used.¹⁷ The gate contact is a p^+n -junction which is biased in reverse direction with a negative gate-source voltage U_G . The respective currents and voltages are explained in the schematic sketch in Fig. 1. All voltages are relative to the zero at the source contact. The *build-in potential* across the depletion layer in the p^+n -junction equals³

$$U_{bi} = \frac{1}{e_0} \left[E_{gap} - k_B T \ln \left(\frac{N_c}{N_d} \right) \right] \quad (1)$$

with E_{gap} as the total band gap energy which is 1.12 eV at room temperature (RT). The quantities N_c and N_d denote the effective density of states of the Si conduction band ($2.8 \cdot 10^{19} \text{ cm}^{-3}$ at RT) and the dopant concentration, respectively. The build-in potential is the same as the total band bending in the junction at thermal equilibrium. For $N_d = 7 \cdot 10^{16} \text{ cm}^{-3}$ (see Results and Discussion), the build-in potential exhibits a slight temperature dependence as it is 0.96 V at RT and 1.09 V at 150 K.

In Fig. 1 the width of the depletion layer W_d varies along the source-drain-channel if the drain-source voltage $U_D \neq 0$.

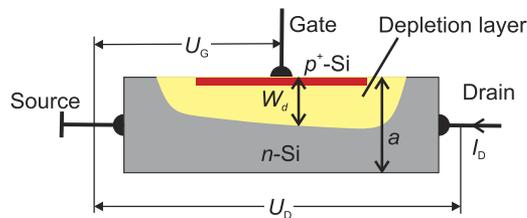


FIG. 1. Schematics of the junction FET with the relevant physical quantities.

The quantity a stands for the total width of the source-drain channel. To characterize the device at low temperatures the input characteristics $I_D(U_G)_{U_D, T}$ and the output characteristics $I_D(U_D)_{U_G, T}$ are recorded where I_D is the source-drain current or in short the drain current. The indices denote the variable parameters.

Three different experimental setups are used to perform the measurements. For recording current-voltage (IV) curves between RT and 160 K, the device is mounted on a ceramic carrier attached onto the cold head of a liquid nitrogen cryostat in UHV. The pins of the device are electrically connected to three isolated terminals what allows to probe currents and voltages with a source-measure unit (Keithley SMU236). The setup gives rise to a stray capacitance at the gate contact and an external leakage resistance due to conductive layers on the carrier and the terminal isolations. From the time constant in which the gate is discharged by a 10 G Ω resistor we deduce a stray capacitance of a few 10 pF. Similarly, discharging the gate without an additional resistor yields a leakage resistance of $10^{13} - 10^{14} \Omega$. For IV measurements below 160 K the device is mounted onto a chip carrier which is attached to the cold head of a He cryostat.

The leakage resistance of the described setups is by far too low to observe internal leakage currents in the sub-attoampere range across the gate depletion layer. Therefore, for measurements of extremely small currents the JFET is freely attached to the tip carrier of a low-temperature scanning tunneling microscope as described in detail in our previous publication.¹⁶ Only source and drain pins are connected to external source meters and the gate contact remains open. The gate-source voltage U_G is initially set to the desired potential by moving the gate into a tunneling contact with an electrode on the defined potential. After subsequent opening the tunneling contact, the temporal variation of the drain current I_D is monitored. By use of the input characteristics of the device the corresponding change of the gate-source voltage U_G is determined. It is found that U_G varies almost linearly in time which indicates a constant leakage current. We determine the intrinsic gate capacitance as 4 pF at 80 K which allows to determine the charge variation on the gate from U_G . With the observed decay of the open gate charge in time the leakage current can be calculated as lost charge per time. With this method the gate voltage can be measured with an accuracy of below 10 μ V which corresponds to approximately 250 elementary charges. Due to the extreme sensitivity of the setup the suppression of any external electric stray fields must be as perfect as possible.

III. RESULTS AND DISCUSSION

A. Direct current IV characteristics

The input and output characteristics of the BF545B at RT are plotted in Fig. 2 in agreement with typical IV-curves from the manufacturer's data sheet.¹⁷ Physical properties of the device can be deduced from the data. For instance, saturation of the drain current occurs for drain voltages which fulfill

$$U_{Dsat} = U_p - U_{bi} + U_G \quad (2)$$

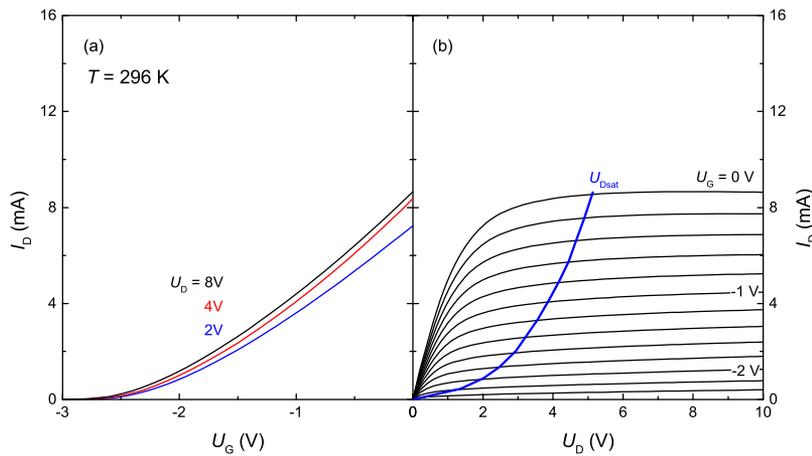


FIG. 2. (a) Input characteristics of the JFET BF545B at RT for drain voltages of 2 V, 4 V and 8 V. (b) Output characteristics at RT. The difference between the gate voltages of neighboring curves is 0.2 V.

with the pinch-off-voltage

$$U_P = \frac{e_0 N_d a^2}{2\epsilon_0 \epsilon_r} \quad (3)$$

where $\epsilon_r = 11.9$ denotes the static dielectric constant of Si.³ As explained later, a donor concentration of $N_d \approx 7 \cdot 10^{16} \text{ cm}^{-3}$ is expected. If the band bending at the drain contact reaches U_P the depletion layer at that contact extends over the entire source-drain channel width a .

The identification of the saturation voltages in Fig. 2(b) is somehow arbitrary because the $I_D(U_D)$ curves exhibit a non-vanishing slope beyond saturation due to thermal heating and channel length effects.³ The blue line represents an intuitive guess which may be used to estimate the channel width a . For $U_G = 0$ a saturation value $U_{Dsat} \approx 5$ V is observed. With the built-in voltage at the p^+n -interface of $U_{bi} = 1$ V, a channel width of $a \approx 260 \pm 30$ nm is calculated from Eqs.(2) and (3).

At $T = 165$ K the drain current increases significantly for small absolute values of U_G as shown in Fig. 3. The negative slopes of the $I_D(U_D)$ curve for large drain currents and voltages

can be attributed to local heating of the device. The decrease of the drain current is related to the dissipated electric power. As expected from Eq.(2), there is hardly any change in the drain voltage at saturation because U_{bi} increases by only 0.1 V when the device is cooled down.

B. Temperature dependence of the input characteristics at charge carrier saturation

The variation of the input characteristics $I_D(U_G)$ in the temperature range between 165 K and 296 K is displayed in Fig. 4 for $U_D = 2$ V. A strong increase of I_D is observed for vanishing gate voltage when the temperature is reduced. As explained later, this behaviour is due to the increase of the electron mobility in the source-drain channel. For larger absolute values of the gate voltage the variation of I_D becomes weaker. At $U_G \approx 2.1$ V, the drain current stays constant and is almost independent of any temperature change. This remarkable result is elucidated when the drain current is described within the constant mobility model and for homogeneous doping. Then, the drain current up to saturation obeys the

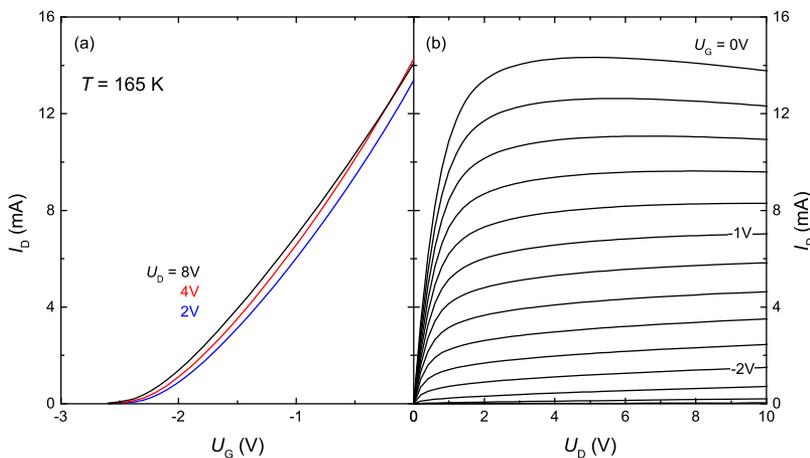


FIG. 3. (a) Input characteristics of the JFET BF545B at 165 K for drain voltages of 2 V, 4 V and 8 V. (b) Output characteristics at 165 K. The difference between the gate voltages of neighboring curves is 0.2 V.

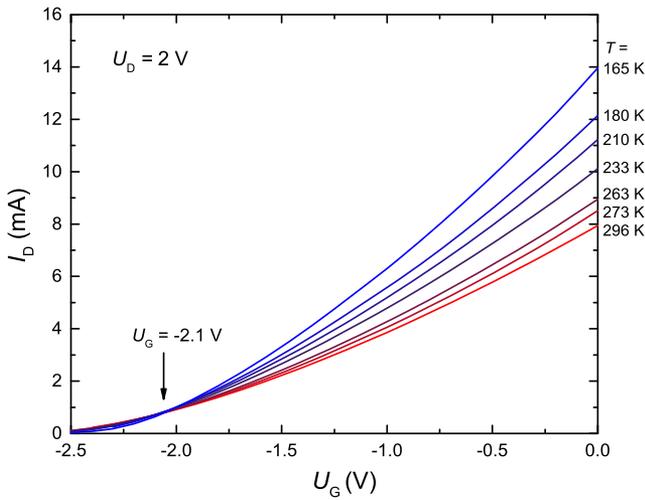


FIG. 4. Input characteristics of the JFET BF545B as a function of temperature for $U_D = 2$ V. In this temperature regime the electron concentration is expected to be constant.

relation³

$$I_D = G(T) \cdot \left[U_D - \frac{2}{3\sqrt{U_P}} \left((U_{bi} + U_D - U_G)^{1.5} - (U_{bi} - U_G)^{1.5} \right) \right] = G(T) \cdot f(T) \tag{4}$$

with

$$G(T) \propto n \mu(T) \tag{5}$$

as the channel conductance. Its temperature dependence is determined by the electron mobility $\mu(T)$ as long as the free electron concentration n is constant. This regime is called charge carrier saturation since all dopant atoms are ionized, i.e., $n \approx N_d$.

In case of silicon, $\mu(T)$ follows a power law T^{-x} with exponents x between 2.33 for low dopant concentrations and almost 0 for degenerate doping. Larger electron concentrations enhance the electron-electron scattering which finally dominates the temperature dependent electron-phonon interaction.

The function $f(T)$ in Eq.(4) exhibits a weak linear temperature dependence governed by $f(T) \approx a(U_G) + bT$ with constants a and b . For $U_G = 0$ the constant a is much larger than bT and the conductance has a temperature dependence similar to the electron mobility. For $U_G < 0$, the constant a decreases and the linear relationship bT start to compensate the T^{-x} dependence of $\mu(T)$.

In Fig. 5 the drain current is plotted as a function of temperature for various gate voltages in a double-logarithmic diagram. The dashed lines represent linear fits to the data. The slopes are equal to the exponents $-x$. Obviously, the sign and the value of the exponent depend significantly on the gate voltage. For zero gate voltage, the relation

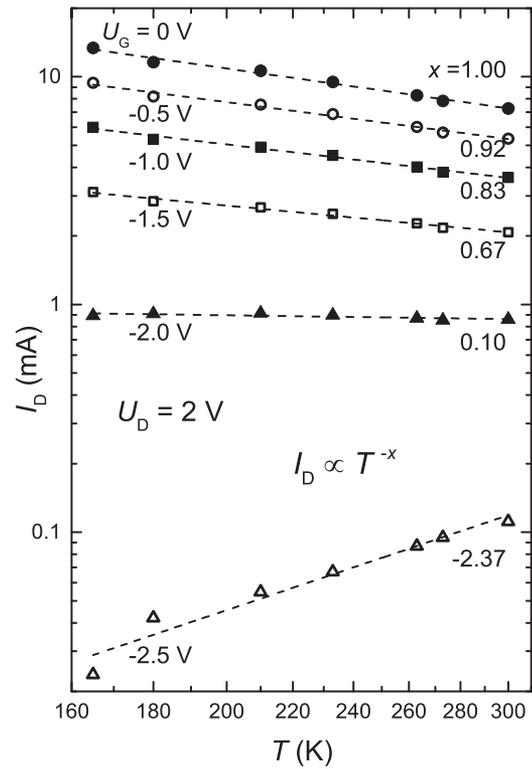


FIG. 5. Drain current I_D as a function of temperature and gate voltage. The slopes represent the negative exponent in the temperature dependence of the electron mobility.

$$I_D(T) \propto T^{-1.0} \Rightarrow \mu(T) \propto T^{-1.0} \tag{6}$$

is found.

We apply the analytical formula for the electron mobility $\mu(T, n)$ in Si from Ref. 18 to estimate the charge carrier concentration in the source-drain channel, i.e.,

$$\mu(T, n) = 2272 \cdot T^{-0.57} + \frac{7.4 \cdot 10^8 T^{-2.33}}{1 + 1.42 \cdot 10^{-11} n T^{-2.54}} \tag{7}$$

with T in K and n in cm^{-3} . The T^{-1} dependence of the mobility requires an electron concentration of $n \approx 7 \cdot 10^{16} \text{ cm}^{-3}$. Hence, the experimental data reveal a relative high donor concentration of the Si material but still well below degenerate doping.

C. Temperature dependence of the input characteristics in the regime of charge carrier freeze-out

For temperatures well below 100 K, free charge carriers start to freeze out. As a consequence, the channel conductance and accordingly the drain current drops exponentially with T . In Fig. 6 the input characteristics is plotted for assorted temperatures in the range between 30 K and 110 K and for $U_D = 2.8$ V. As before, we take the I_D at zero gate voltage to analyse the temperature dependence of the electron conductivity.

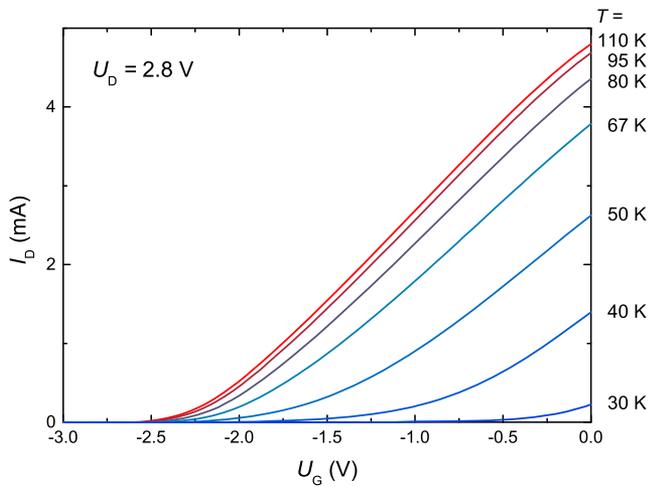


FIG. 6. Input characteristics of the JFET BF545B as a function of temperature for $U_D = 2.8$ V. In this temperature regime the electron concentration drops exponentially due to freezing-out of the charge carriers.

In Fig. 7 the respective drain current is plotted as a function of reciprocal temperature in an Arrhenius-type diagram. It demonstrates that the decrease of the electron concentration is governed by an exponential function below 50 K. In that region, it is expected that

$$I_D(T) \propto n(T) = \sqrt{\frac{N_d N_c}{2}} \exp\left[-\frac{\Delta E}{2k_B T}\right] \quad (8)$$

where the activation energy ΔE is the energy difference between the conduction band minimum and the single donor ground state level, i.e., the ionization energy of the donor atom. According to Eq.(7) the temperature dependence of the

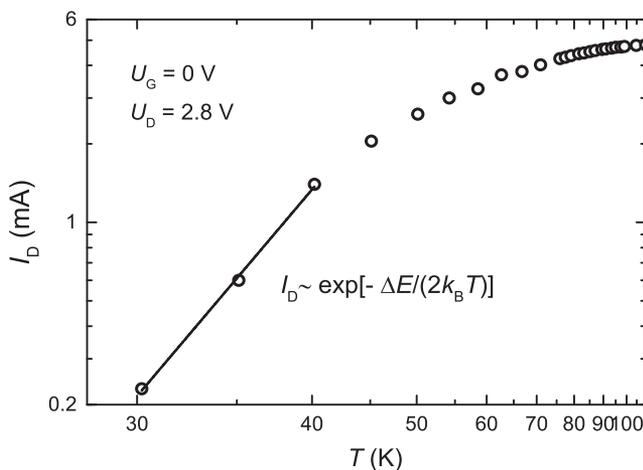


FIG. 7. Arrhenius plot of the drain current I_D versus temperature in the freeze-out regime. From the slope of the linear fit the donor ionization energy of 40 meV can be deduced from ΔE .

mobility can be neglected in the freeze-out regime. The prefactor in front of the exponential in Eq.(8) has a weak $T^{0.75}$ temperature dependence due to the effective density of states. If we ignore the $T^{0.75}$ prefactor an activation energy of 38 meV is calculated from the linear fit in Fig. 7. Including $T^{0.75}$ yields $\Delta E = 33$ meV.

We underestimate the ionization energy due to heating of the device. Most likely, the temperature of the device at cryostat temperature of 30 K is slightly higher. Hence, we expect $\Delta E \approx 40$ meV with an uncertainty of ± 10 meV. The value agrees well with the ionization energy of phosphorus atoms as donors in Si which is *n*-Si of 46 meV.³

In Fig. 7, the temperature dependence of the drain current between 50 and 100 K is again governed by the electron mobility which decreases with lower temperature due to the dominating electron-ionized donor scattering.

D. Temperature dependence of the gate leakage current

To determine the leakage through the gate depletion layer the device is brought into the thermally isolated environment of a low-temperature STM. At first, the gate contact is set on a defined reverse potential ($U_G = -2$ V) and it is then permanently opened. From the measured temporal variation of the drain current the decrease of the gate charge with time is calculated using the known input characteristics and gate capacity.

With lower temperatures the leakage current I_L drops exponentially and reaches a constant value below 160 K. This is demonstrated in the Arrhenius-type diagram in Fig. 8 which plots the normalized leakage current $I_L/T^{1.5}$ as a function of the reciprocal temperature. As explained below, the division by $T^{1.5}$ takes the weak temperature dependence of

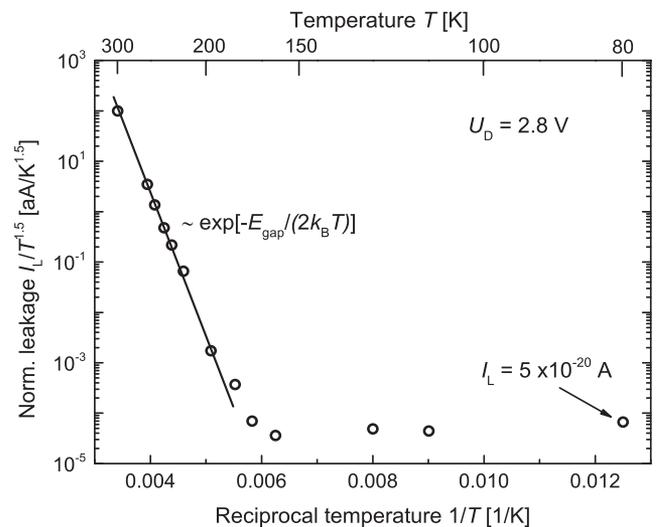


FIG. 8. Arrhenius plot of the normalized gate leakage current $I_L/T^{1.5}$ versus temperature. From the slope the band gap energy of 1.13 eV can be determined according to the SRH theory.

exponential prefactor into account. The leakage current arrives at the outstandingly small value of $5 \cdot 10^{-20}$ A at 80 K. Such currents may be due to discharging the gate by cosmic radiation or by parasitic currents through high-resistive layers.

Leakage in a *pn*-diode at very low temperatures is due to a generation current induced by thermal creation of electron-hole pairs at deep level traps in the depletion layer. We apply the Shockley-Read-Hall (SRH) theory^{3,19,20} to yield its temperature dependence. Assuming mid-gap traps in a non-degenerate semiconductor the theory predicts a leakage current density under reverse conditions of

$$j_L = \frac{e_0 W_d}{\tau} n_i \quad (9)$$

with W_d as the depletion layer width and τ as the generation lifetime which both are slowly varying functions of temperature. However, the intrinsic charge carrier density n_i depends exponentially on the temperature, i.e.,³

$$n_i(T) \propto T^{1.5} \exp\left[-\frac{E_{\text{gap}}}{2k_B T}\right]. \quad (10)$$

The solid line in Fig. 8 represents a linear fit to the exponential decrease over seven orders of magnitude. The slope corresponds to a gap energy of 1.13 ± 0.05 eV which is in perfect agreement with the expected Si band gap energy of 1.16 eV at $T = 0$ K.

In addition, the results in Fig. 8 demonstrate that JFETs at low temperatures can be used as impedance converters with an exceptionally large input resistance which is by orders of magnitude higher than what is heretofore available. As described earlier, also the bandwidth of the device is remarkably high.¹⁶ At a bandwidth of 10 kHz, a sensitivity of 250 elementary charges is observed.

IV. SUMMARY

The input and output characteristics as well as the gate leakage current of the JFET BF545B is studied in the temperature range between 30 and 300 K. The thermal variation of the drain current can be attributed to the electron conductance in the source-drain channel. As long as all donors are ionized, the temperature dependence of the drain current at zero gate voltage allows the determination of the dopant concentration. However, for a certain gate voltage the drain current becomes almost temperature independent. When the charge carriers begin to freeze out, the ionization energy of the dopant atoms can be determined from the drain current. A value of 40 meV is found in accordance to phosphorus as donor atom.

The exponential decrease of the gate leakage current with lower temperatures is observed over seven orders of magnitude to values in the 0.01 attoampere range under open-gate conditions. There is clear evidence that the leakage current is due to the generation current in the reverse biased *p*⁺*n*-junction since the data reproduce the Si band gap energy when the Shockley-Read-Hall theory is applied. Impressively, the results demonstrate that cooled JFETs can be used as input transistors of ultra-sensitive electrometers and impedance converters with current loads in the sub-attoampere range.

ACKNOWLEDGMENTS

We thank Prof. Dr. Axel Lorke and Dennis Oing (University of Duisburg-Essen) for the technical support and the opportunity to use a He-cryostat. The financial support by the Deutsche Forschungsgemeinschaft through No. SFB1242: *Non-equilibrium dynamics of condensed matter in the time domain* is gratefully acknowledged.

REFERENCES

- ¹A. Edmundo Gutierrez, M. Jamal Deen, and C. L. Claeys, *Low Temperature Electronics: Physics, Devices, Circuits, and Applications* (Academic Press, 2000).
- ²A. N. Gerritsen and F. van den Burg, *Physica* **17**, 930 (1951).
- ³S. M. Sze and K. K. Ng, *Physics of semiconductor devices*, 3rd ed. (Wiley-Interscience, 2006), p. 23; pp. 80-100; pp. 374-400.
- ⁴S. S. Sesnic and G. R. Craig, *IEEE Trans. on Electron Devices* **ED-19**, 933 (1972).
- ⁵M. J. Churchill and P. O. Lauritzen, *Solid St. Electron.* **14**, 985 (1971).
- ⁶L. M. Rucker, E. R. Chenette, and A. Ambrozy, *Solid St. Electron.* **21**, 596 (1978).
- ⁷R. Singh and B. J. Baliga, *Solid St. Electron.* **39**, 821 (1996).
- ⁸W. Nawrocki, *Czech. J. Phys.* **46**(Suppl. S5), 2747 (1996).
- ⁹R. T. Goldberg, M. D. Jhabvala, R. K. Kirschman, S. Wang, D.-H. Gwo, and J. A. Lipa, *Electrochem. Soc. Proc.* **95-9**, 428 (1995).
- ¹⁰K. Sreelakshmi and M. Satyam, *Cryogenics* **36**, 325 (1996).
- ¹¹M. Iliescu and M. Culcer, *Rom. Rep. Phys.* **52**, 167 (2000).
- ¹²A. Pullia, F. Zocca, S. Riboldi, D. Budjas, A. DAndragora, and C. Cattadori, in *IEEE Nuclear Science Symposium Conference Record N30-42* (IEEE, 2008), p. 2056.
- ¹³E. R. Huppi, *Microchim. Acta* **93**, 281 (1987).
- ¹⁴K. Lindström and N.-G. Holmer, *Phys. Scr.* **5**, 279 (1972).
- ¹⁵B. Michel, L. Novotny, and U. Dürig, *Ultramicroscopy* **42-44**, 1647 (1992).
- ¹⁶P. Graf, M. Flebbe, D. Utzat, H. Nienhaus, and R. Möller, *Rev. Sci. Instrum.* **88**, 084702 (2017).
- ¹⁷NXP data sheet, document identifier: BF545A-BF545B-BF545C, NXP B.V. (2011).
- ¹⁸N. D. Arora, J. R. Hauser, and D. J. Roulston, *IEEE Trans. on Electron Devices* **ED-29**, 292 (1982).
- ¹⁹W. Shockley and W. T. Read, Jr., *Phys. Rev.* **87**, 835 (1952).
- ²⁰C.-T. Sah, R. N. Noyce, and W. Shockley, *Proc. IRE* **45**, 1228 (1957).

Temperature dependent electrical characteristics of a junction field effect transistor for cryogenic sub-attoampere charge detection

Kavangary, Anahita; Graf, Paul; Azazoglu, Hüseyin; Flebbe, Meike; Huba, Kornelia; Nienhaus, Hermann; Möller, Rolf

This text is provided by DuEPublico, the central repository of the University Duisburg-Essen.

This version of the e-publication may differ from a potential published print or online version.

DOI: <https://doi.org/10.1063/1.5077039>

URN: <urn:nbn:de:hbz:464-20190312-145042-1>

Link: <https://duepublico.uni-duisburg-essen.de:443/servlets/DocumentServlet?id=48340>

License:



This work may be used under a [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license.

Source: AIP Advances 9, 025104 (2019); Published Online: 11 February 2019