NOISE DUE TO DONORS IN n-CHANNEL SILICON JFETS
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Abstract—We have measured the noise due to donors in n-channel silicon JFETs at temperatures near liquid nitrogen temperature. The noise showed an activation energy of about $1.3E_0$, where $E_0$ is the activation energy of the donor centers. This is compatible with theory.

While studying the temperature dependence of the noise parameter $R_{eq}$ in short-channel (4.1 µm) n-channel silicon JFETs, we found a sharp increase in the noise resistance $R_n$ at temperatures near 77°K. We interpreted this increase in the noise as generation-recombination noise, caused by the fact that not all donors are ionized at low temperatures.

The devices were low-current low-saturation-voltage devices, so that heating effects were rather insignificant. The noise was frequency-independent up to at least 10 MHz, indicating a very small time constant $\tau$ of the generation-recombination process. Figure 1 shows an example of the measurements. Here $\ln R_n$ is plotted vs $e/kT$; the full-drawn curve gives the measurements and the dotted line is corrected for the background thermal noise of the device. We see that the corrected curve is a straight line with an activation energy of 0.061 eV. Other measurements gave similar results and similar values.

The theory of the effect is well known([1, 2]). Let the donors give rise to recombination and generation rates $r(n) = \rho n^2$ and $g(n) = \gamma (N_d - n)$, respectively, where $N_d$ and $n$ are the donor and the electron concentrations, respectively, both per unit volume. Here $\gamma$ and $\rho$ are constants, $\gamma$ depends on temperature as const. $\exp(-E_0/kT)$, where $E_0$ is the activation energy of the donors in eV, so that the activation energy of $R_n$ is about 1.3 $E_0$.

The equilibrium electron concentration $n_0$ follows from

$$\gamma (N_d - n_0) = \rho n_0^2.$$  

(1)

This leads to a time constant $\tau$ and a variance ($\text{var} n$) of $n$

$$\tau = 1/(2\rho n_0 + \gamma) = (1/\gamma)n_0(2N_d - n_0);$$

$$\text{var} n = \alpha n_0 = n_0(N_d - n_0)/(2N_d - n_0).$$  

(2)

The spectral intensity of the current noise for a non-saturated device is then given as[1, 2]

$$S_I(f) = (4ep/L^2)I_dV_0\sigma_1(1 + \omega^2\tau^2)$$  

(3)

where $e$ is the electron charge, $\mu$ the mobility, $L$ the channel length, $I_d$ is the drain current and $V_d$ the drain voltage; for saturated devices $V_d$ must be replaced by the saturation voltage $V_{ds}$. The noise resistance of the device is defined by

$$4kT_0R_n = S_I(f)/g_m^2$$  

(3a)

where $g_m$ is the transconductance of the device and $T_0$ is

Fig. 1. $R_n$ vs $e/kT$ for device FD110 No. 1 $V_d = 3.0$ V, $V_g = -0.5$ V, $f = 4$ MHz, $T_0 = 298°K$. Full drawn curve gives the measurements; the dotted curve is corrected from the data by subtracting a fixed thermal noise resistance of 75 ohms to get the net effect of the $g-r$ noise of the donors. The slope of the dotted curve gives an activation energy of 0.061 eV.

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room temperature. Since in our measurements $\omega^2 \tau^2 \ll 1$, the noise resistance $R_n$ is proportional to $\alpha \tau$.

If we put $u = n_0/N_d$, we may write

$$\alpha \tau = \left(1/\gamma(u(1-u)(2-u)^2)\right)$$ (4)

where $u$ follows from (1) as

$$u = 1/2\delta[-1 + (1 + 4/\delta)^{1/2}]$$ (4a)

and $\delta = \gamma/(\rho N_d)$. Figure 2 shows $\gamma \alpha \tau = u(1-u)(2-u)^2$ as a function of $\delta$. We see that this function is independent of $\delta$ near $\delta = 1$ and that it varies as $1/\delta$ for very large $\delta$. The activation energy of $\alpha \tau$ and hence of $R_n$ thus lies between $E_0$ and $2E_0$ electron volts.

We now return to Fig. 1. We made the transition from the full-drawn curve to the dotted curve by subtracting a constant noise resistance $R_n$ due to thermal noise. If we could have made a more accurate determination of $R_n$ as a function of the temperature $T$, we might have seen a gradual change in the slope of the dotted line, as required by Fig. 2. However, we were unable to do so. Nevertheless, the results obtained with our crude correction show reasonable compatibility with the above theory.

The theory leading to eqn (3) is a low-field theory that needs to be corrected for field-dependent mobility effects. We will return to that problem in a subsequent paper but wish to point out that this does not affect the presence of the parameter $\alpha \tau$ and hence does not affect the temperature dependence of $R_n$. There is also some temperature dependence of $g_m$ but this only slightly alters the dependence of $R_n$ upon $T$, since $\alpha \tau$ varies as $\exp(\varepsilon E_0/kT)$ whereas $g_m$ varies as a low power of $T$.

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REFERENCES