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ON THE "EXCESS WHITE NOISE" IN MOS TRANSISTORS

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Special silicon MOS transistors are fabricated to demonstrate that the proposed "excess white noise" attributed to the mobility fluctuation does not exist. The previously observed excess noise over the white thermal noise is shown to be caused by the a 1/f-type noise component due to noise measurements at insufficiently high frequencies on devices which have very high 1/f noise.

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I. INTRODUCTION

van der Ziel and coworkers[1-4] have reported the detection of white noise in excess of the white thermal noise in MOS transistors, based on the observation of drain voltage and current dependences on the output noise power. Their experimental data indicated rapidly increasing I_{eq} (equivalent saturated diode noise current at the drain) as the drain voltage, V_D, or current, I_D, approach their saturation values, V_{DS} or I_{DS}, at a constant gate voltage V_G. Both the simple thermal noise theory[5] and the more exact theory including the effect of substrate impurity doping[6,7] predict a montonically decreasing I_{eq} as I_D and V_D approach their saturation values.

In their work[3,4] it was postulated that the observed "excess white noise" is due to the mobility fluctuation caused by ionized impurity scattering, and that higher substrate impurity concentration would give higher excess white noise. Unfortunately, the substrate impurity concentration levels of the devices used in references 1 to 4 were not known. This uncertainty makes their comparison with the "low" impurity concentration devices used by Klaassen and Prins[7] difficult to assess.

Since mobility reduction due to ionized impurity scattering comes from the randomness of the spatial distribution of the impurity ions, the mobility fluctuation noise is a second order effect and it is expected to contribute negligible noise in addition to those already included in the thermal noise due to random scattering of electrons and holes.

Some earlier experimental work[6] did not indicate the presence of an excess white noise component in the thermal noise region, although the data taken were referred to the gate input, R_{gn}, which did not give as clear an indication of the presence of an excess component as I_{eq}. More recently, the lack of an excess white noise component was reconfirmed and reported (in footnote of reference 8) when the data was taken at $f > 1$MHz in low noise devices. I_{eq} was observed to decrease monotonically with **increasing** V_D and stayed constant when $V_D \geq V_{DS}$ (the saturation value). However, devices used there had relatively low substrate impurity concentration.

In this paper, special silicon MOS transistors are fabricated in our laboratory with high substrate doping and low 1/f surface noise to allow a detailed investigation of the existence of any excess noise over the predicted thermal noise. The devices are listed in Table I. Based on the measurements on these devices, it is shown experimentally that the excess white noise component does not exist if noise measurements are made at sufficiently high frequencies where the 1/f component is completely masked by the thermal noise component. It is demonstrated by low frequency noise measurements that the observed excess white noise is indeed the 1/f component due to insufficiently high frequency of noise measurements. The generation-recombination noise (f^{-2}-type) could also lead to the observation of the "excess white noise," but this component is generally lower than the 1/f component in the megahertz region.

II. THEORY

The purpose of the following analysis is to show that the presence of a small 1/f noise component in the thermal noise of the MOS transistor could lead to the observations reported in references 1 to 4. On the other hand, if the frequency is high enough so that the 1/f noise component makes negligible contribution, then the noise of the MOS transistor is expected to follow the thermal noise theory.

A. Thermal Noise

The simple thermal noise theory which neglects the effect of the bulk charge shows that[4,5,7]

$$I_{eq} = \frac{2}{3} I_{eqo} \left[\frac{V_G'}{2V_G' - V_D} + 1 - \frac{V_D}{V_G'} \right] \qquad (1)$$

where

$$I_{eqo} = \frac{2kT}{q} g_{do} \qquad (1A)$$

$$g_{do} \simeq \frac{\mu Z C_o}{L} V_G' = \text{drain conductance at } V_D = 0. \qquad (1B)$$

$V_G' = V_G - V_T$ = effective gate voltage (1C)

V_D = drain voltage (1D)

μ = effective carrier mobility in the surface channel (1E)

Z = channel width (1F)

L = channel length (1G)

$$C_o = \frac{K\varepsilon}{x_o} \qquad (1H)$$

x_o = gate oxide thickness (1I)

At saturation, $(V_D = V_G')$, and

$$I_{eq}(V_D = V_G') = I_{eqs} = \frac{2}{3} I_{eqo} \qquad (2)$$

A plot of (1) will show that I_{eq} monotonically decreases as V_D increases from 0 to $V_{DS} = V_G'$.

Although the thermal noise theory which includes the effect of the bulk charge[6,7] into the I-V characteristics of the device is more exact, a numerical calculation of the V_D dependence of I_{eq} still shows that I_{eq} decreases monotonically as V_D increases. Furthermore a normalized plot of I_{eq} vs V_D is almost identical to the normalized plot of equation (1) for all practical ranges of oxide thicknesses, substrate doping and gate biases. We therefore limit the analysis to the simple noise theory equations.

B. 1/f Noise Theory

The mechanism of the 1/f noise in MOS-T transistors has been a subject of intensive study recently. Sah and Hielscher,[9] demonstrated its surface origin by correlations of its noise power with the density of surface states in the $Si\text{-}SiO_2$ interface. Abowitz, Arnold, and Leventhal[10] also showed that the 1/f noise is proportional to the surface states density. Christensson, Lundstrom, and Svensson,[11] worked out three cases using McWhorter's tunneling model of channel carriers tunneling into the $Si\text{-}SiO_2$ interface surface states, to explain the drain voltage dependences of R_{gn} in commercial MOS transistors. Flinn, Bew, and Berz observed that R_{gn} is relatively insensitive to V_D in the 1/f noise region. In references 8 and 10, the authors also reported that R_{gn} is very weakly dependent on V_D or I_D. On the other hand, R_{gn} is a sensitive function of V_G as shown in reference 9.

For the present purpose, the physical model of the 1/f noise is bypassed and an empirical theory is derived based on the assumption that the equivalent gate noise resistance, R_{gn}, of the

1/f noise component is independent of V_D. This assumption, based on the results of the quoted papers in the preceding paragraph, will also be verified in the truly 1/f noise region given in the last part of the experimental section.

From this assumption we write the drain voltage dependence of the 1/f noise as

$$R_{gn} = \frac{\text{constant } (V_G')}{f} \tag{3}$$

where f is the frequency. The equivalent saturated drain noise current is related to R_{gn} by

$$I_{eq} = \frac{2kT}{q} g_m^2 R_{gn} \tag{4}$$

where the transconductance, g_m, is

$$g_m = \frac{\mu Z C_o}{L} V_D \tag{5}$$

From (3) to (5)

$$I_{eq} = \frac{A}{f} V_D^2 \tag{6}$$

where $A = A(V_G')$ and is not a function of V_D or I_D.

C. Combination of Thermal and 1/f Noise

Since the noise sources are generally independent, the total noise power due to the 1/f source and the thermal source is just

$$I_{eq(total)} = I_{eq(1/f)} + I_{eq(thermal)} \tag{7}$$

Using (1) and (6), equation (7) becomes

$$I_{eq(total)} = \frac{A(V_G')}{f} V_D^2 + \frac{2}{3} I_{eqo}(V_G')\left[\frac{V_G'}{2V_G' - V_D} + 1 - \frac{V_D}{V_G'}\right]. \tag{8}$$

For a given V_G', both $A(V_G')$ and $I_{eqo}(V_G')$ can be determined experimentally. $I_{eqo}(V_G')$ is obtained at $I_{eq}(V_D = 0)$ and it can also be computed from (1A) using the measured g_{do}. $A(V_G')$ is determined at a given V_G' and at low frequency where $A(V_G')V_D^2/f$ dominates over the thermal noise term in (8).

Equation (8) can be used to demonstrate the V_D dependence of $I_{eq(total)}$ and to explain the experimental observations in references 1 to 4. After determining $A(V_G')$ and $g_{do}(V_G')$ at a given V_G', a family of I_{eq} vs V_D curves is obtained using (8). Figure 1 shows the curves calculated at three different frequencies for the device TA2-1 whose experimental spectrum is shown in Fig. 3 and its V_D dependence in Fig. 4. The unknown quantity A is experimentally obtained at $f_o = 4$ KHz in Fig. 3, where the 1/f noise component is more than an order of magnitude above the thermal noise level. Since Fig. 3 was measured at $V_D = V_{DS} = V_G'$, A is obtained with the aid of (8) using $V_D = V_G'$, and the last term neglected. The effective gate voltage, V_G', was calculated from the I-V characteristics, by matching the actual g_{do} and I_{DS} with the simple MOS-T theory.

III. EXPERIMENTS

A. Devices

Three types of devices were fabricated to clarify the important points in this paper. All devices in each of the three groups have essentially identical characteristics due to the well-controlled low surface state fabrication conditions. The use of commercial devices is avoided because the 1/f noise extends beyond the megahertz region. Furthermore the physical parameters and the device history are usually not available.

B. Measurements

Direct I_{eq} measurements was employed. The measuring circuit is similar to that discussed by Champlin[12] for measuring the noise of forwardly biased diodes. In the MOS transistors, the drain resistance is usually comparable to the load resistance of the noise diode, therefore some modifications of the circuit and the procedure outlined in reference 12 are necessary to obtain accurate results for drain voltages below saturation. This method is quite accurate even near $V_D = 0$ or thermal equilibrium and avoids the noise measurement difficulties of small V_D indicated by several authors.[7,10,11]

C. Results

Figure 2 is shown to demonstrate that for a high surface state device (QA1-1), the 1/f noise is so high that the thermal noise level is not reached even at 1.5 MHz. Actually in Fig. 2, the low-frequency thermal noise level, ($2/3\ I_{eqo}$), could not be extended beyond the 1.5 MHz region because the drain conductance starts to deviate from the low frequency value. At high frequencies, where the thermal noise dominates, $g_d = g_d(f)$, and therefore $I_{eq} = I_{eq}(f)$.

Figure 3 shows a lower surface state device (TA2-1), in which the thermal noise level is barely reached at 1 MHz. In Fig. 4 the drain voltage dependence of TA2-1 is experimentally measured at 10, 100, and 1500 KHz to show the contrast of the thermal and the non-thermal noise dependences. This is in agreement with the curves which were calculated from equation (8) using the parameters of device TA2-1 and with those observed in references 1 to 4.

Figure 5 shows the spectra of a high substrate impurity device, RB2-1. The high substrate doping was chosen in order to find out if the excess white noise exists as previously claimed.[2-4] In contrast to devices QA1-1 and TA2-1, the device RB2-1 has a thicker oxide and a shorter channel length. These parameters were chosen to minimize the high frequency effects on the device parameters. Furthermore, suitable processing was employed to reduce the 1/f noise so that the validity of the thermal noise theory can be demonstrated at a relatively low frequency. Figure 6 shows the V_D dependence of I_{eq} at f_o = 40 KHz. This result unequivocally demonstrates that the high doping level of the substrate <u>does not</u> produce the so called excess white noise.

Figure 7 is presented to demonstrate the validity of our previous assumption on the V_D dependence of the 1/f noise. Devices QA1-1 and TA2-1 were chosen for this particular experiment because they exhibit large 1/f noise. The thermal noise component was subtracted from the measured $I_{eq(total)}$. The dashed curve shows the thermal noise component of QA1-1. It is clear in this figure that the 1/f noise component is extremely low for low values of V_D. While the V_D-axis is normalized, actual values are used for the I_{eq}-axis in order to avoid crowding of the two lines. The square law V_D dependence of I_{eq}, as predicted by (6), is obeyed fairly well. The deviation near saturation is due to the non-ideal I-V characteristics of the device, and the deviation of the points for low V_D results from the subtraction of two nearly equal quantities to separate the 1/f component from the total (thermal plus 1/f) noise measured.

IV. CONCLUSIONS

It is conclusively demonstrated that the so called "excess white noise" does not exist in MOS-T's even for devices with high substrate dopings. The "excess white noise" reported previously is shown to be due to the presence of the 1/f-type noise component. Finally, it is also demonstrated that the I_{eq} due to the 1/f noise in MOS-T's has a square law V_D dependence for $V_D \leq V_{DS}$.

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TABLE 1

Device #	Orientation, Doping (cm^{-3})	L (microns)	Z (microns)	x_o (micron)
QA1-1	[111] N 5×10^{14}	50	1128	.126
TA2-1	[100] P 5×10^{15}	50	1128	.120
RB2-1	[100] N 7×10^{16}	25	1128	.260

FIGURE CAPTIONS

Fig. 1 Theoretical curves illustrating the effect of the 1/f noise component on I_{eq} near the thermal noise region. The physical parameters used are those of device TA2-1.

Fig. 2 Noise spectra of a high surface state MOS Transistor showing the 1/f noise component still appreciable at 1 MHz.

Fig. 3 Noise spectra of a low surface state MOS Transistor showing the thermal noise level barely reached at 1 MHz.

Fig. 4 Drain-voltage dependence of I_{eq} for TA2-1 at different values of f_o to experimentally illustrate the effect of the 1/f noise component on the total drain current noise.

Fig. 5 Noise spectra of a high substrate doping which have very low surface states. The thermal noise levels are reached at relatively low frequencies.

Fig. 6 Drain-voltage dependence of I_{eq} for a high substrate doping MOS Transistor to show that the "excess white noise" does not exist even for a highly doped substrate.

Fig. 7 Experimental data showing the square law V_D dependence of I_{eq} for the 1/f noise in MOS Transistors.

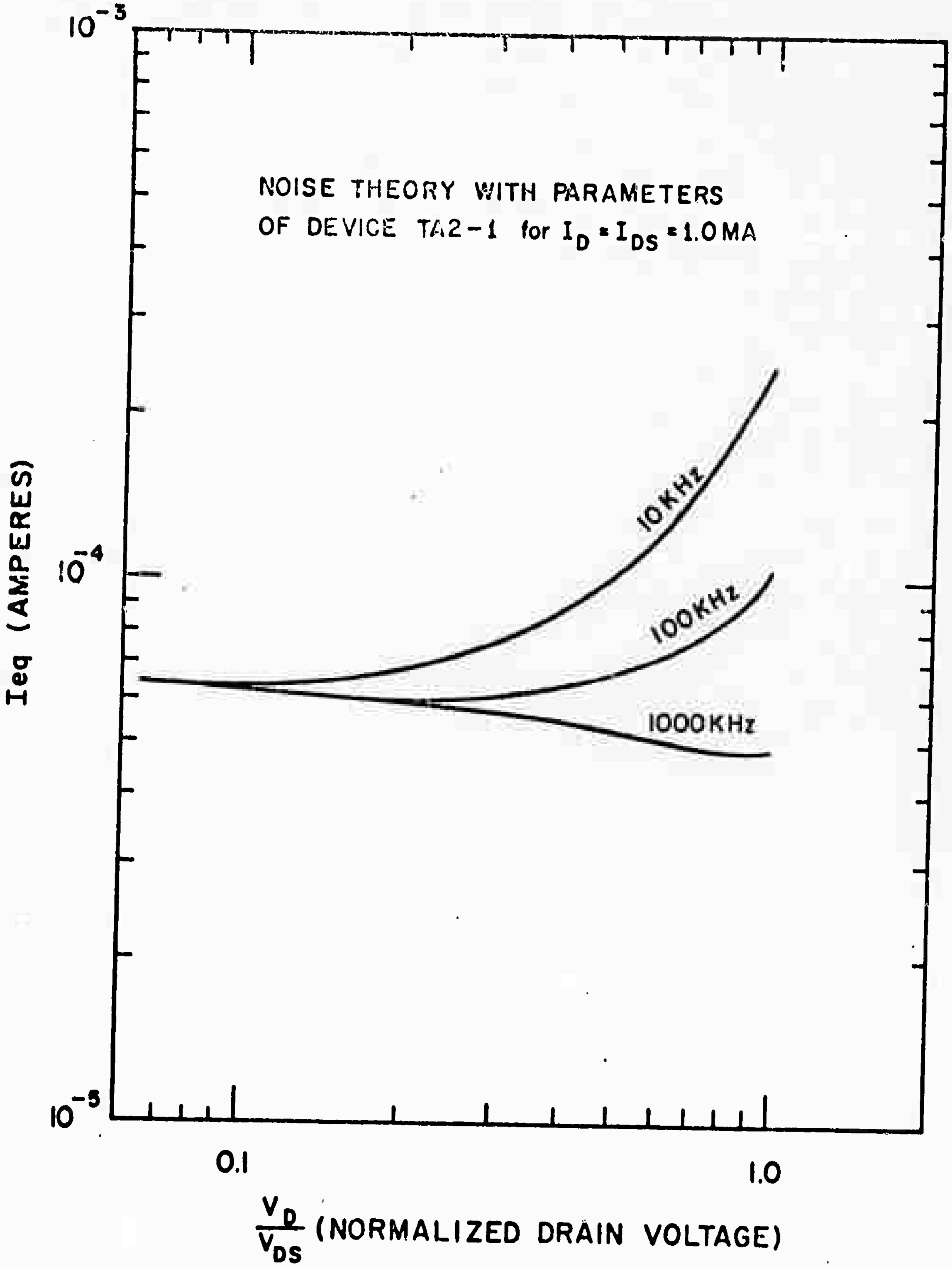

NOISE THEORY WITH PARAMETERS
OF DEVICE TA2-1 for $I_D = I_{DS} = 1.0$ MA
10KHz
100KHz
1000KHz
Ieq (AMPERES)
10^{-3}
10^{-4}
10^{-5}
0.1
1.0
$\frac{V_D}{V_{DS}}$ (NORMALIZED DRAIN VOLTAGE)

Figure 1

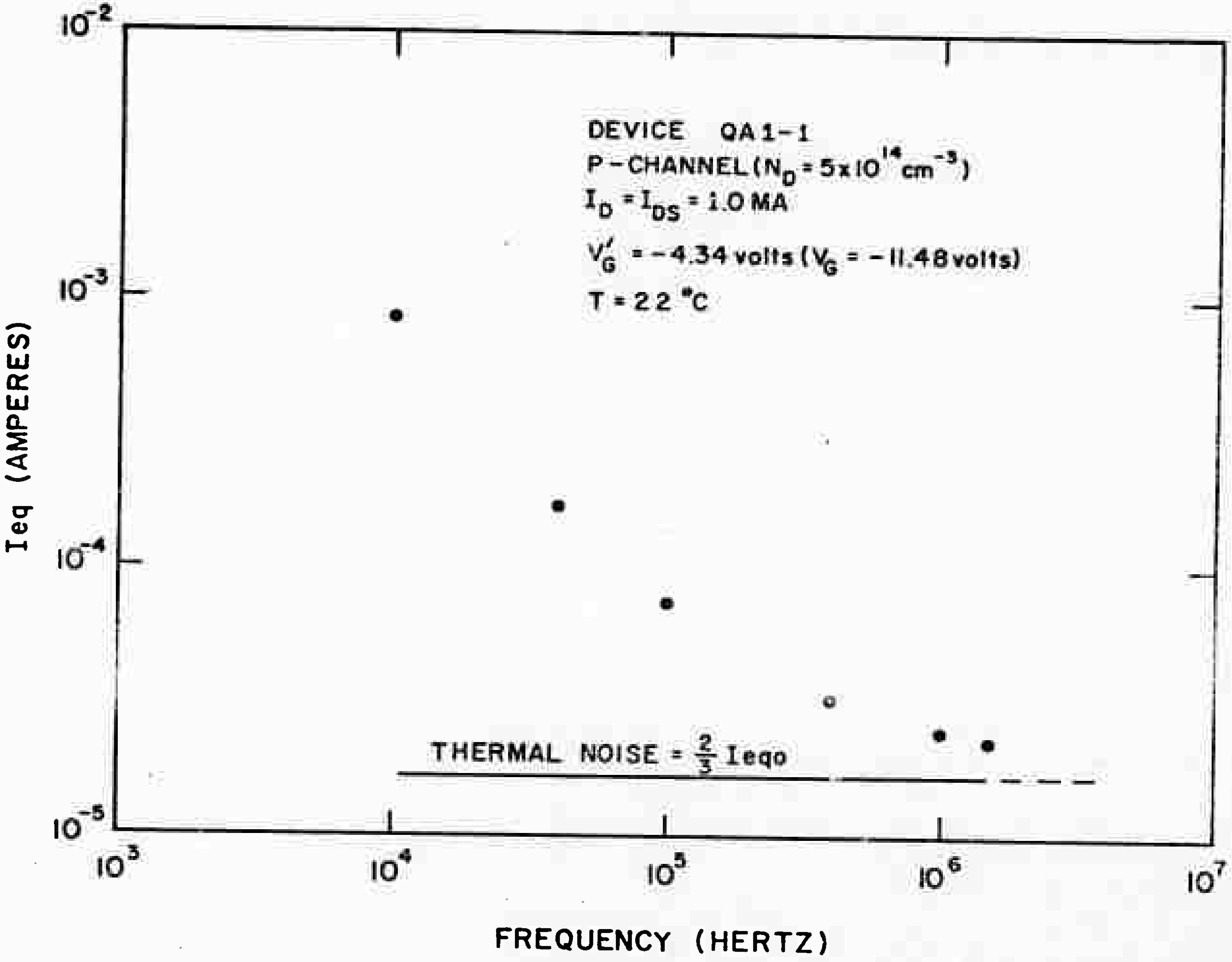

DEVICE QA1-1
P-CHANNEL ($N_D = 5 \times 10^{14} cm^{-3}$)
$I_D = I_{DS} = 1.0$ MA
$V_G' = -4.34$ volts ($V_G = -11.48$ volts)
T = 22 °C
THERMAL NOISE = $\frac{2}{3}$ Ieqo
Ieq (AMPERES)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
FREQUENCY (HERTZ)

Figure 2

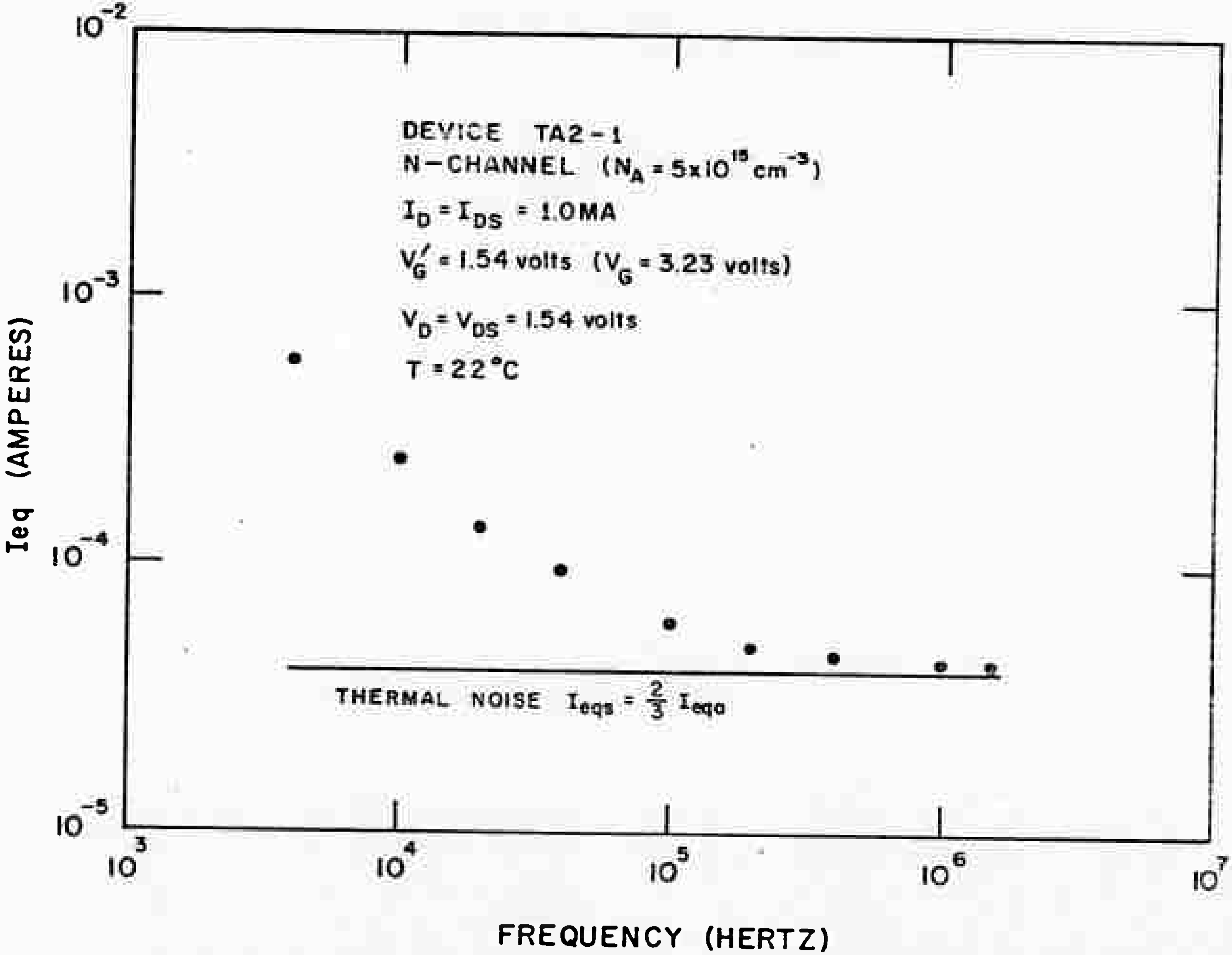

DEVICE TA2-1
N-CHANNEL ($N_A = 5 \times 10^{15} cm^{-3}$)
$I_D = I_{DS} = 1.0MA$
$V_G' = 1.54$ volts ($V_G = 3.23$ volts)
$V_D = V_{DS} = 1.54$ volts
$T = 22°C$
THERMAL NOISE $I_{eqs} = \frac{2}{3} I_{eqo}$
Ieq (AMPERES)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
FREQUENCY (HERTZ)

Figure 3

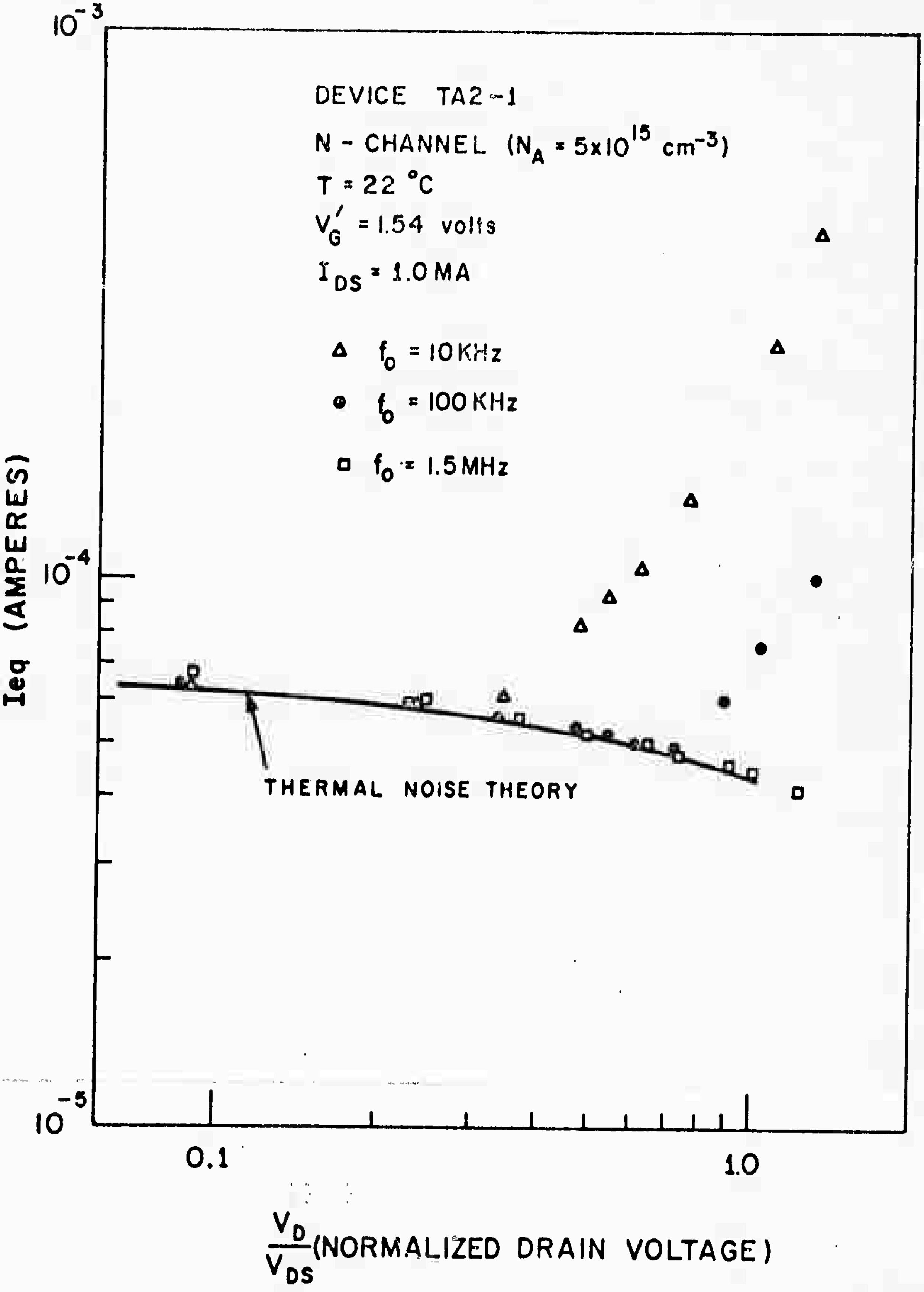

DEVICE TA2-1
N - CHANNEL ($N_A = 5\times10^{15}$ cm^{-3})
T = 22 °C
$V_G' = 1.54$ volts
$I_{DS} = 1.0$ MA
△ f_o = 10 KHz
● f_o = 100 KHz
□ f_o = 1.5 MHz
THERMAL NOISE THEORY
10^{-3}
10^{-4}
10^{-5}
Ieq (AMPERES)
0.1
1.0
$\frac{V_D}{V_{DS}}$ (NORMALIZED DRAIN VOLTAGE)

Figure 4

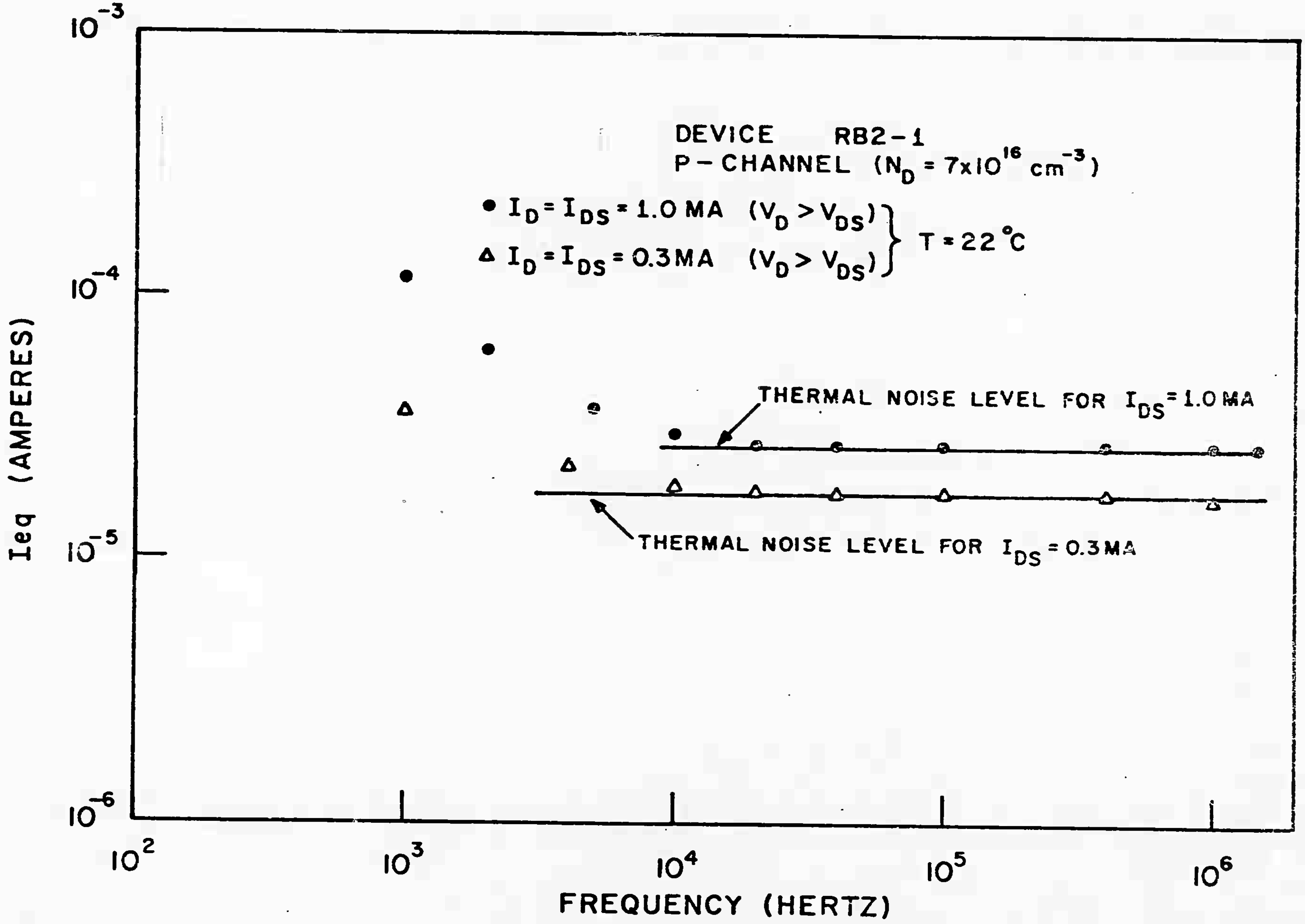

DEVICE RB2-1
P-CHANNEL ($N_D = 7 \times 10^{16}$ cm^{-3})
● $I_D = I_{DS} = 1.0$ MA ($V_D > V_{DS}$)
△ $I_D = I_{DS} = 0.3$ MA ($V_D > V_{DS}$)
T = 22 °C
THERMAL NOISE LEVEL FOR $I_{DS} = 1.0$ MA
THERMAL NOISE LEVEL FOR $I_{DS} = 0.3$ MA
Ieq (AMPERES)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
10^5
10^6
FREQUENCY (HERTZ)

Figure 5

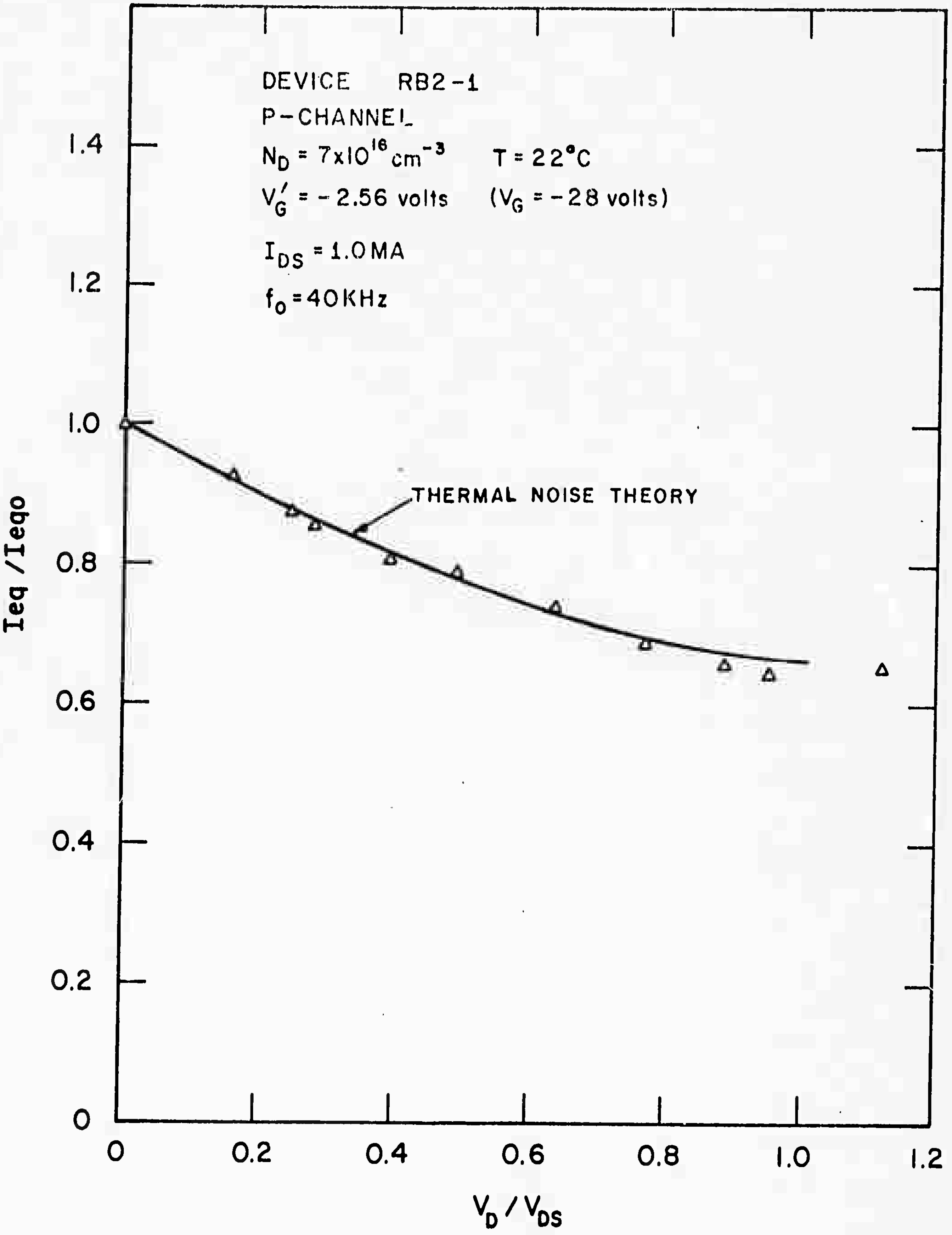
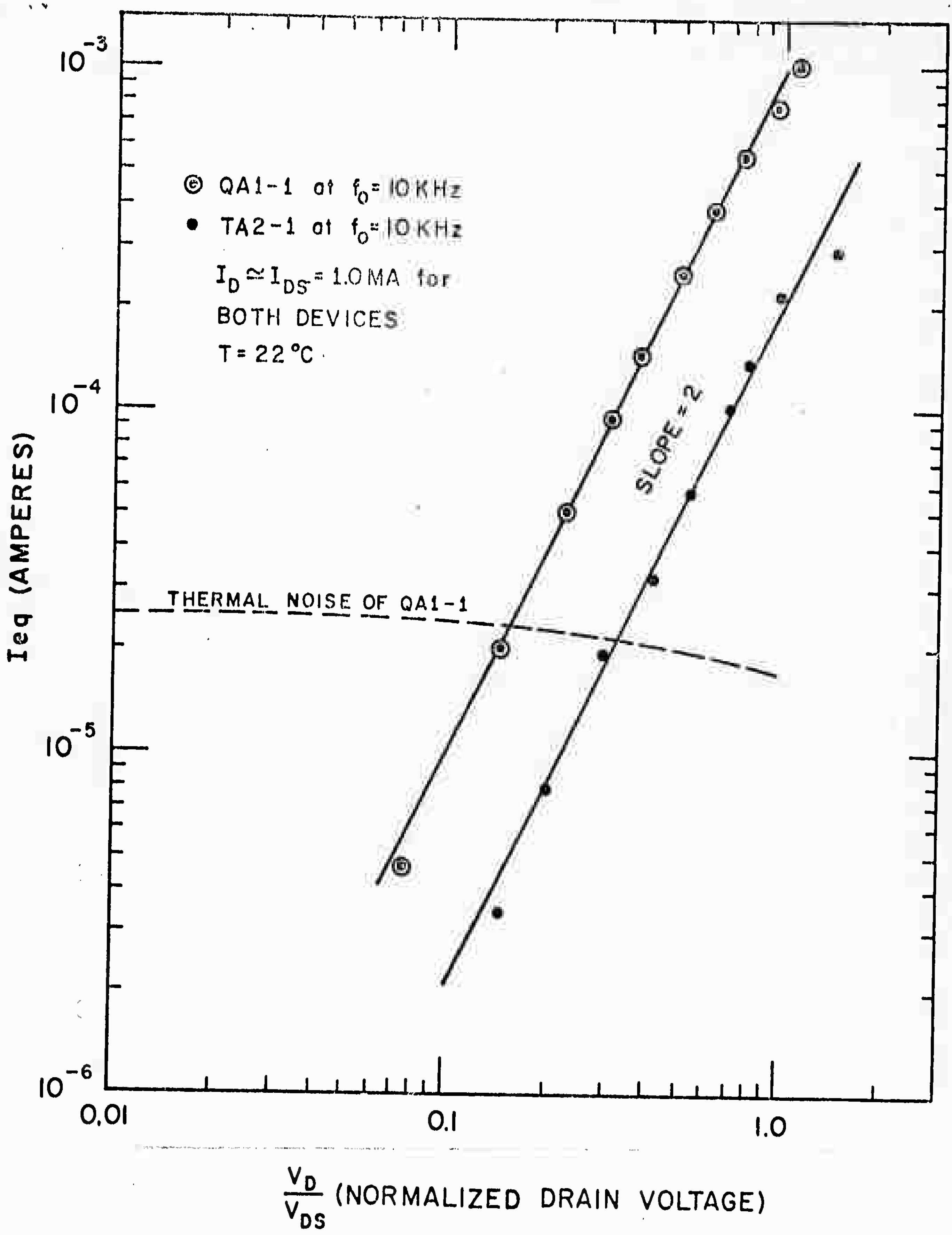

DEVICE RB2-1
P-CHANNEL
$N_D = 7\times10^{16} cm^{-3}$ T = 22°C
$V_G' = -2.56$ volts ($V_G = -28$ volts)
$I_{DS} = 1.0$ MA
$f_0 = 40$ KHz
THERMAL NOISE THEORY
Ieq /Ieqo
V_D / V_{DS}
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Figure 6



⊙ QA1-1 at f_0 = 10 KHz
● TA2-1 at f_0 = 10 KHz
$I_D \simeq I_{DS}$ = 1.0 MA for BOTH DEVICES
T = 22 °C
SLOPE = 2
THERMAL NOISE OF QA1-1
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Ieq (AMPERES)
0.01
0.1
1.0
$\frac{V_D}{V_{DS}}$ (NORMALIZED DRAIN VOLTAGE)

Figure 7