Shot Noise Modeling in MOSFETs under Sub-threshold Condition

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Abstract

The minimization of device size increases the importance of high-frequency noise problem. The shot noise in MOSFET, which is ignored in old investigations, has been reported in some recent works.

We have extended the shot noise model of p-n diode to that of MOSFET and calculated spectrum intensity of shot noise generated at source-bulk interface. At low frequency, shot noise is weak and exponentially depends on gate voltage. At high frequency about GHz, however, shot noise is independent on the voltage and quite larger than that of low-frequency.

1. Introduction

Recently, with decreasing device size and its driving power, the noise amplitude tends to be enhanced. Among noise sources in MOSFETs, the 1/*f* and thermal noise are dominant at low frequency and have been studied in detail experimentally and theoretically[1-2]. Another type of noise, the shot noise, has been expected to be quite small and ignorable in the past[3].

The shot noise is generated when carriers flow across the potential barrier. Figure 1 shows the cross section of n-MOSFET with two major sources of shot noise. The gate leak current I_G causes enhancement of shot noise under $t_{OX} < 2$nm and sufficient gate voltage V_G[4-6]. The other source is I_D at p-n junction potential barrier. Obrecht *et al*.[7-8] calculated that the shot noise become dominant at short channel length about $L \sim 0.5\mu$m.

In this paper, we extend the shot noise model of p-n diode to n-MOSFET in weak inversion. Then we perform calculation of shot noise by 2-D device simulator MEDICI, and discuss about bias, channel length, or frequency dependency.

2. Shot Noise Modeling for Calculation

Van der Ziel[1] reported that the shot noise in p-n$^+$ diode is generated when electrons cross junction potential barrier. The electron flow is consists of three components as shown in Figure 2: 1) Electrons from n$^+$ to p region. They lead current $I+I_0$ where I is total current and I_0 is saturation current. 2) Electrons from p to n$^+$ region corresponding to current I_0. 3) Electrons from n$^+$ and back scattered into n+ region. The current shot noise spectrum density $S_I(f)$ is described as

$$S_I(f) = 2q(I + 2I_0) + 4kT\left[g(f) - g_0\right], \quad (1)$$

where $g(f)$ and g_0 are AC and DC conductance, respectively. The first term is shot noise caused by the above components 1 and 2. The second term is caused by the enhancement of conductance by component 3.

In MOSFET, there are two p-n junctions and the conductance includes that of source-bulk and drain-bulk diffusion layer, and channel region. The conductance of diffusion layers is frequency-dependent and that of channel region is independent. Therefore, the frequency-dependent part of MOSFET AC conductance is about a half of conductance of each diffusion layer. In the case of n-MOSFET, only source-bulk junction contributes to shot noise because conduction electrons flow from source to drain. Thus the second term of Eq. 1 should be estimated from doubled AC conductance.

To predict shot noise spectrum in drain current of n-MOSFET, we perform computer simulation by using MEDICI. We calculate drain current I_D and AC conductance, and then estimate shot noise spectrum from above model.

3. Results and Discussion

Figure 3 is surface potential distribution between source and drain under V_D = 1V and valuable V_G. The height of potential barrier decreases with V_G as shown in the inset. Therefore, the drain current is expected to generate shot noise at sub-threshold region.

Figure 4 is an example of calculated shot noise spectrum $S_I(f)$ where channel length $L = 0.5\mu$m, channel width $W = 1.0\mu$m, V_D = 1.0V, and V_G = 0.2~0.4V. Calculated shot noise spectrum is made of two components: frequency-independent part caused by sub-threshold current, and frequency-dependent part at higher frequency caused by back scattering of electrons. At low-frequency region, the former frequency-independent part is dominant so that $S_I(f) \sim 2qI_D$ (dotted line). Around GHz and higher frequency region, on the other hand, the later frequency-dependent part becomes dominant and $S_I(f) \sim 4kTg(f)$ (dashed line). When V_G approaches to V_{th} =0.49V, low-frequency noise increases rapidly although high-frequency noise is almost constant.

Figure 5 is calculated shot noise amplitude at 1kHz and 10GHz for different L and V_D, plotted against V_G - V_{th}. As shown in this figure, the shot noise intensity is almost independent on V_D and is increased with decreasing L. The low-frequency shot noise (white symbols) is exponentially enhanced by V_G. At high-frequency of 10GHz (colored symbols), on the other hand, the intensity is quite large and constant at small V_G.

4. Conclusion

We have extended shot noise model for p-n diode to MOSFET. The shot noise in drain current is generated at the potential barrier of source-bulk interface when V_G is sufficiently weak. Then we estimate shot noise spectrum in MOSFET by using our modeling.

Calculated noise spectrum is made of two components: low-frequency part of $S_I(f) \sim 2qI_D$ and high-frequency part of $S_I(f) \sim 4kTg(f)$. The later is almost independent on V_G and larger than the former.

This result indicates that the shot noise may be serious problem at GHz or higher frequency because the noise never decreases even at quite small bias. On small power driving of future devices, this result should be noticed.

References

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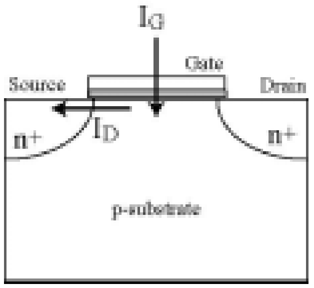

Fig. 1 Two major shot noise sources in n-MOSFET. The arrow indicates the current which generates shot noise.

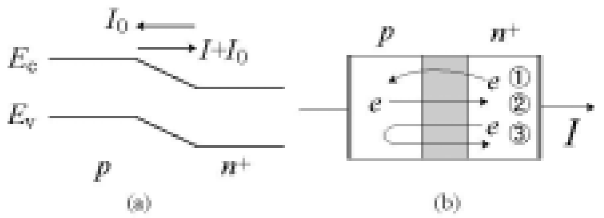

Fig.2 (a)The energy band figure and (b) three components of electron flow in p-n$^+$ junction.

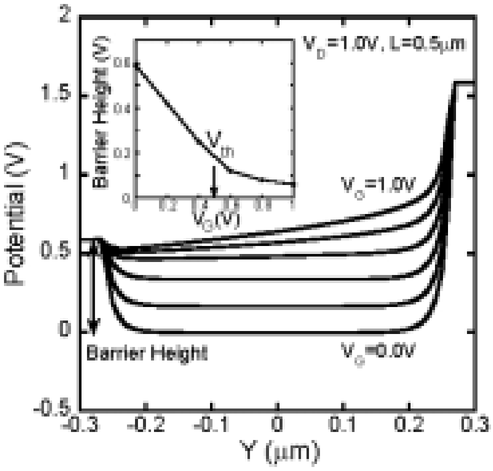

Fig.3 (a)Surface potential distribution and (b)V_G dependency of potential barrier height.

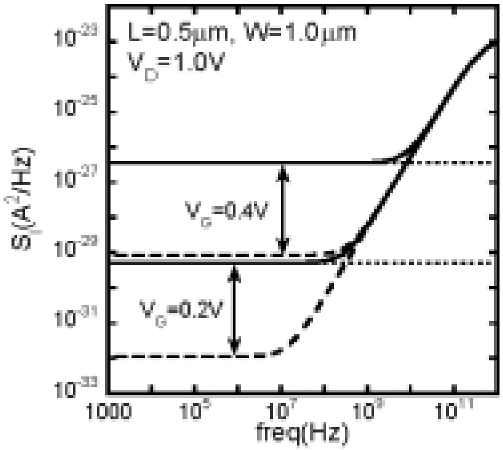

Fig.4 The shot noise spectrum calculated by MEDICI. The dotted line is 1st term of eq. 1, dashed line is 2nd term, and solid line is $S_I(f)$.

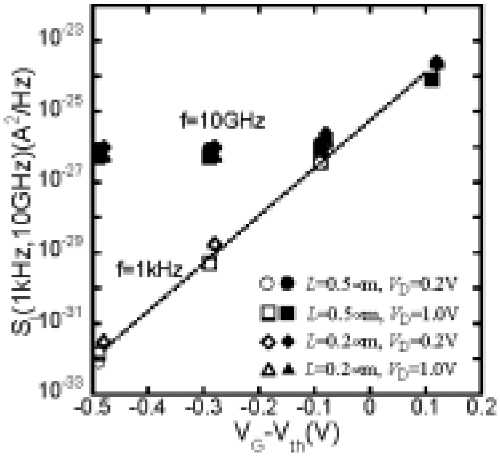

Fig.5 Calculated shot noise intensity at f = 1kHz (white symbol) and f = 10GHz (colored symbol).

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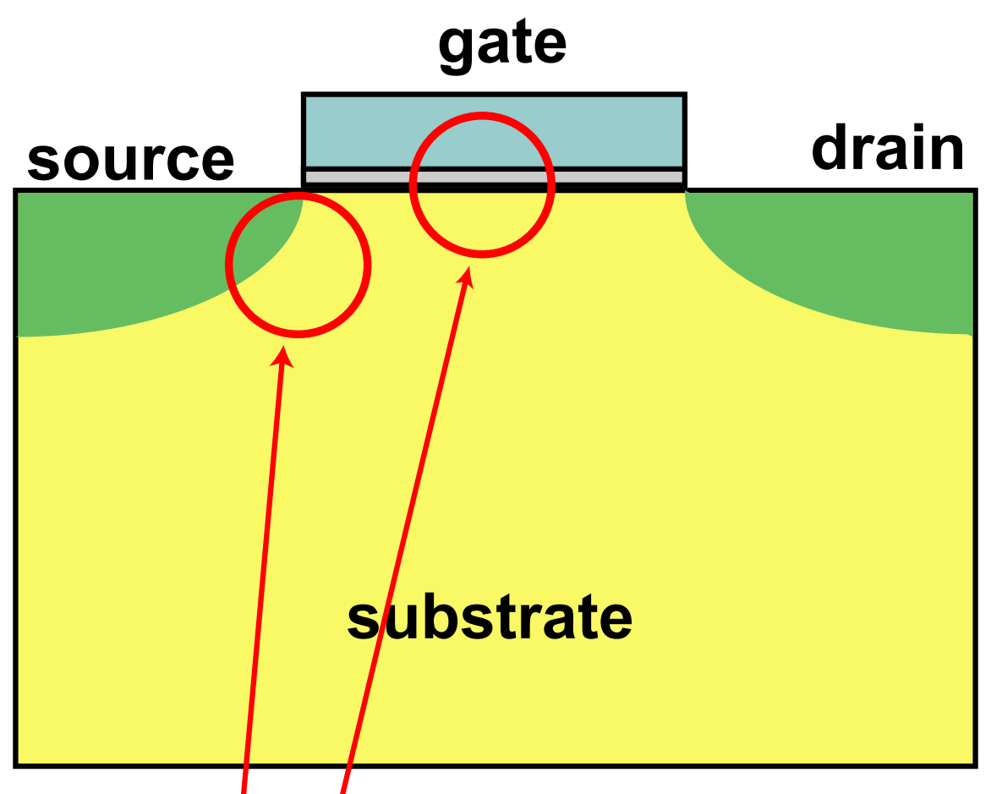
Background

RF Noise sources in micro devices

In previous works, the 1/f and thermal noise are discussed in detail as major noise in MOSFETs.

Recently, the minimization of device size increases the importance of RF noise probrem.
The noise sources which are ignored in old investigations become observable in micro devices.

In short-channel MOSFET, shot noise generated at p-n junction is predicted to be dominant instead of channel thermal noise.



noise source	generated noise
thin gate oxide	gate current noise gate indued noise
p-n junction	junction shot noise

noises significant in short-channel MOSFETs

Necessity of New Noise Modeling for small devices

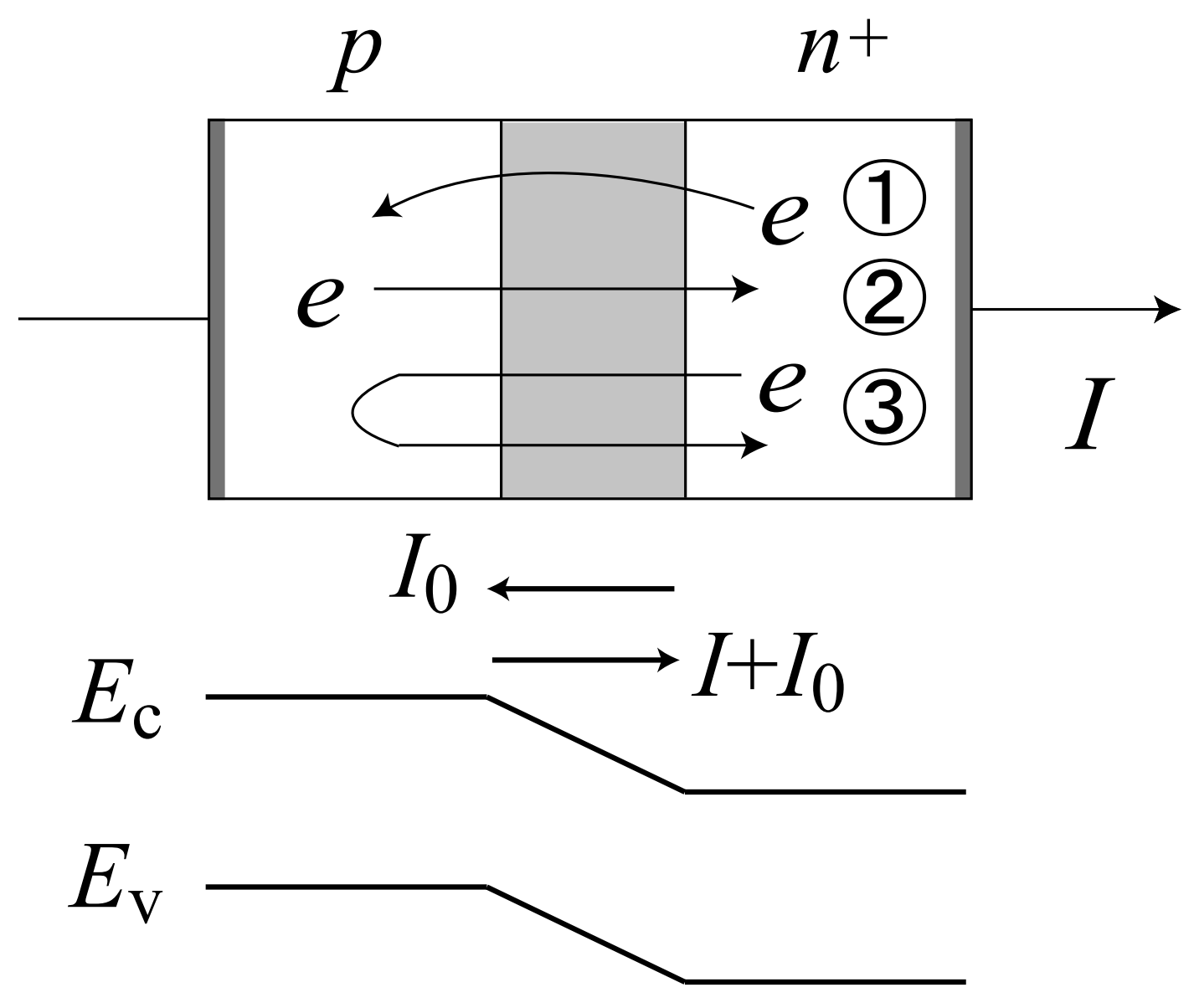
Purpose

We extend the shot noise model of p-n diode to n-MOSFET to predict high-frequency characteristics of shot noise.

We perform calculation of shot noise by 2D device simulator MEDICI and discuss bias, channel length, or frequency dependency.

Shot Noise Modeling

Theoretical model for p-n diode



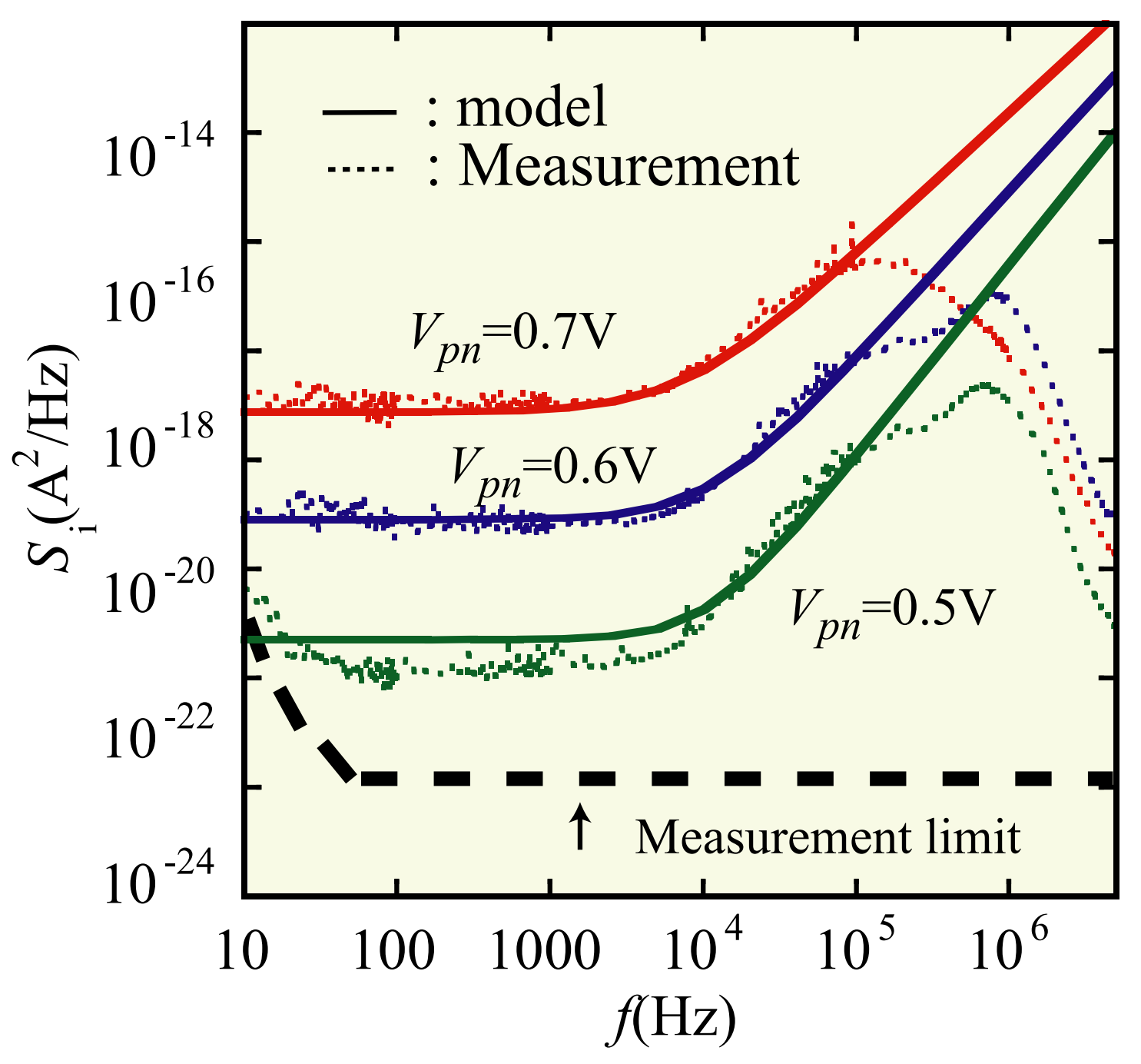
Three components of conduction carrier in p-n⁺ diode

1. **Electrons from n⁺ to p region:**
   carrying current $I + I_0$
2. **Electrons from p to n⁺ region:**
   carrying current I_0
3. **Electrons from n⁺ and scattered backward to n⁺:**
   contribution only to AC conductance

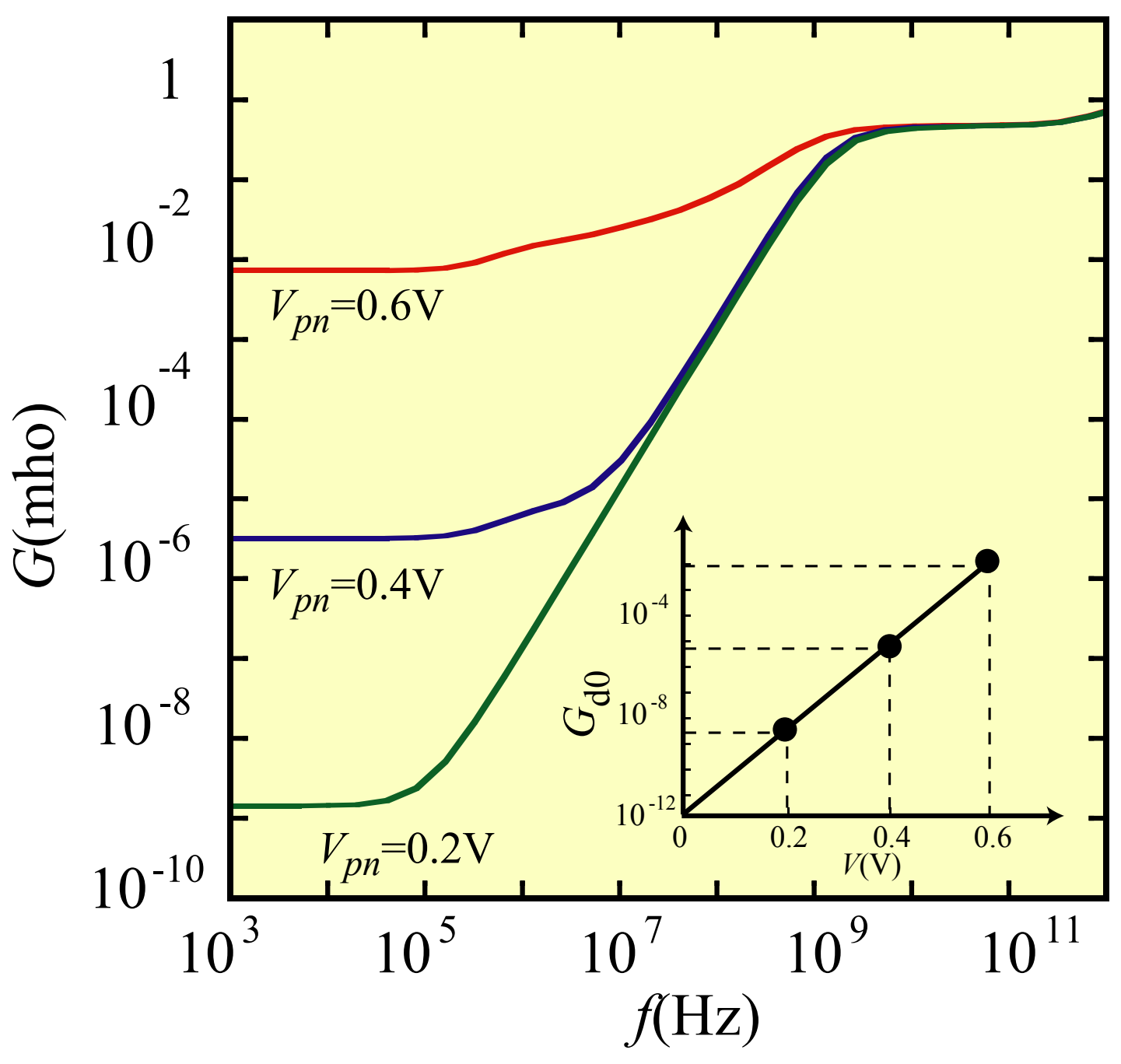
Structure and energy band configuration of p-n junction.

Shot noise model equation

$$S_I(f) = \underbrace{2q(I + 2I_0)}_{\text{(components 1 and 2)}} + \underbrace{4kT(g(f) - g_0)}_{\text{(compontnt 3)}}$$



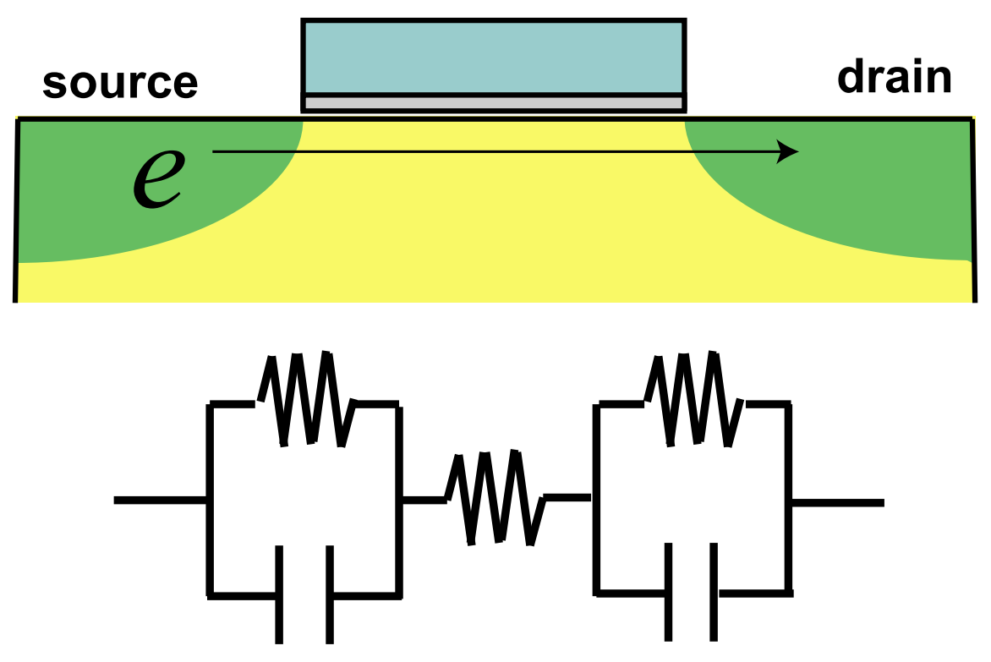
Measured noise spectrum (by Hara) and calculated shot noise in p-n diode



AC conductance G calculated by MEDICI in p-n diode

Calculated results from the model equation agree with measurement.

Expansion for n-MOSFET



equivalent circuit of MOS drain-channel-source region

low freq. region:	**conductances of two junction layers are dominant. (conductance is constant)**
middle freq. region:	**frequency-dependent conductane of junction layers are dominant. (conductance increases with f)**
high freq. region:	**conductance of channel region is dominant. (conductance is saturated)**

Shot noise:
generated when carriers cross potential barrier.

Conducting electrons:
flows from source to drain region through channel surface.

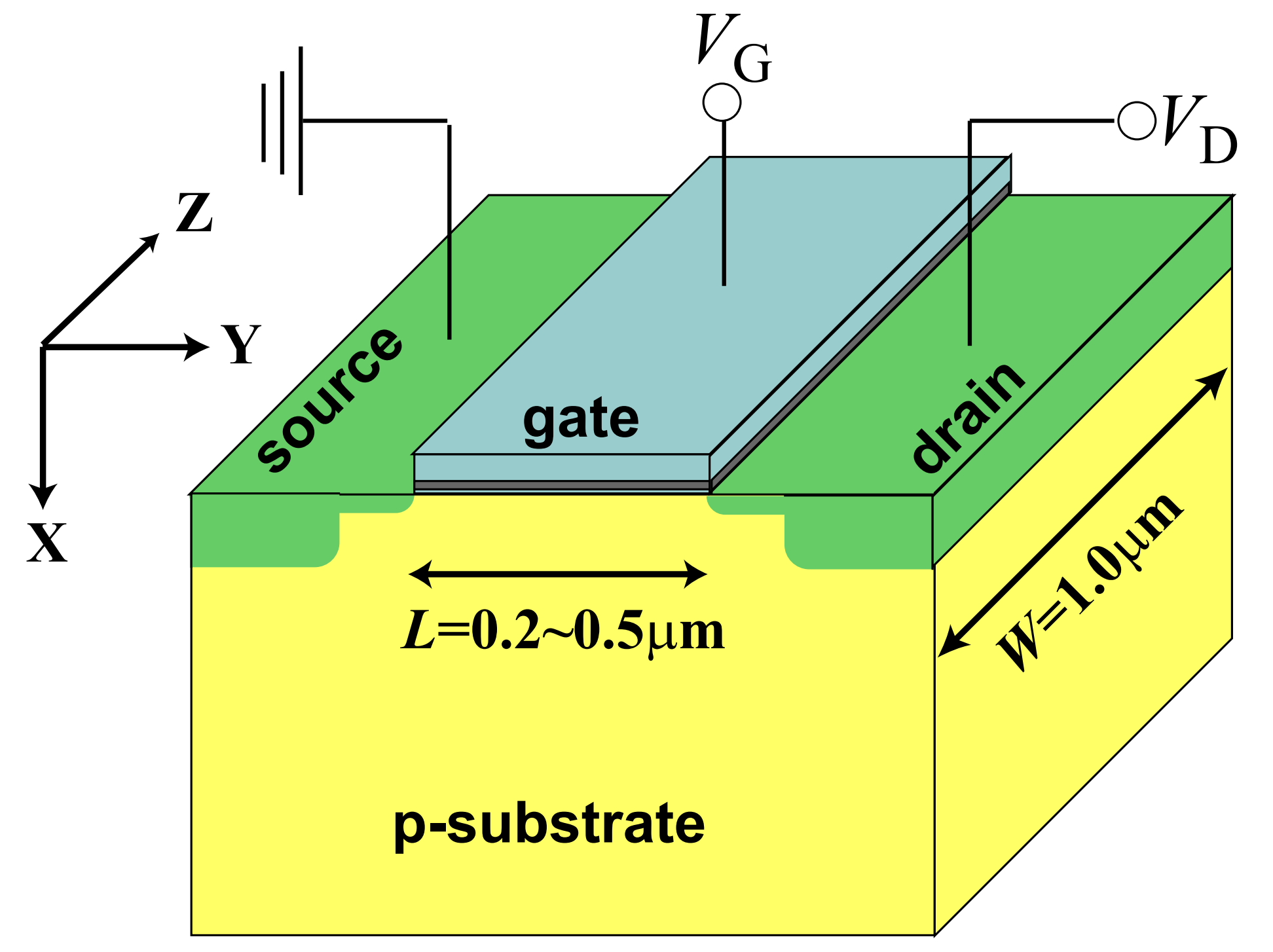
Only source-bulk interface contributes to shot noise generation.

Shot noise model equation for MOSFET

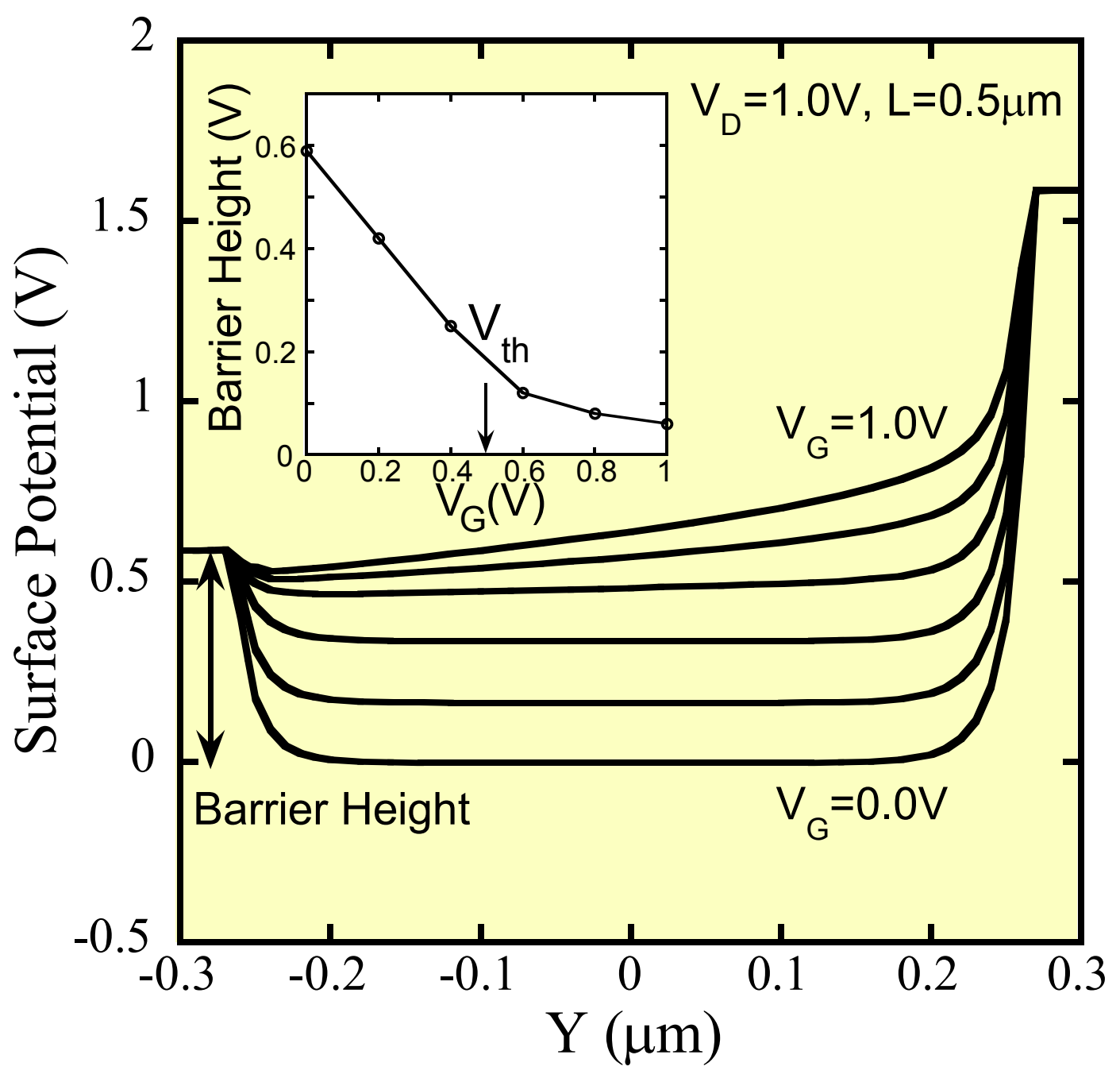
$$S_I(f) = 2q(I + 2I_0) + 8kT(g(f) - g_0) \quad \left(\text{below the frequency where the conductance saturates}\right)$$

Results of calculation

Characteristics of MOSFET



n-MOSFET model for 2D device simulator MEDICI

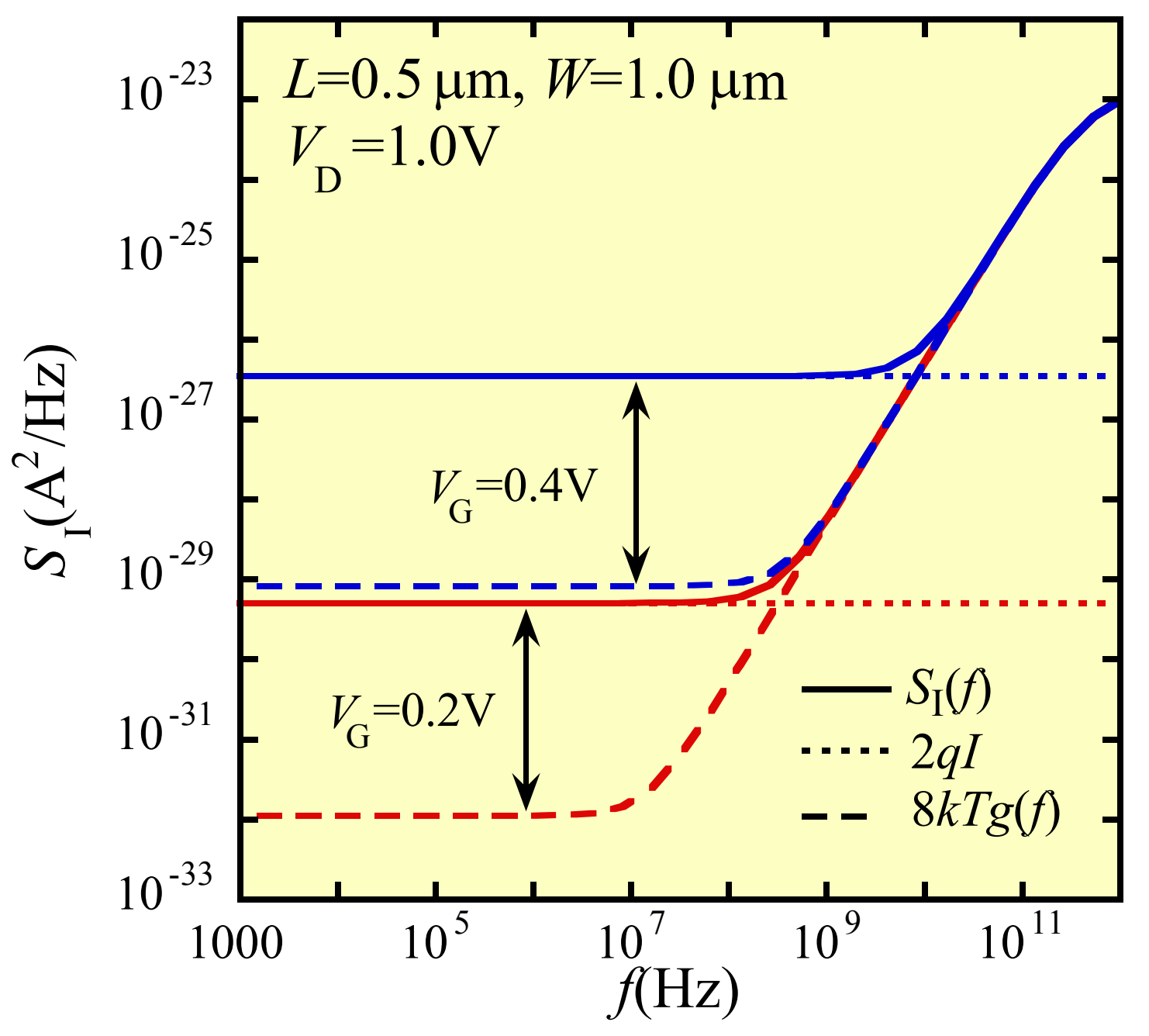


Surface Potential distributions

Potential barrier height decreases with applying gate voltage.

Shot noise should be generated under weak V_G condition.

Shot Noise Characteristics



Gate Voltage dependency

low frequency region:

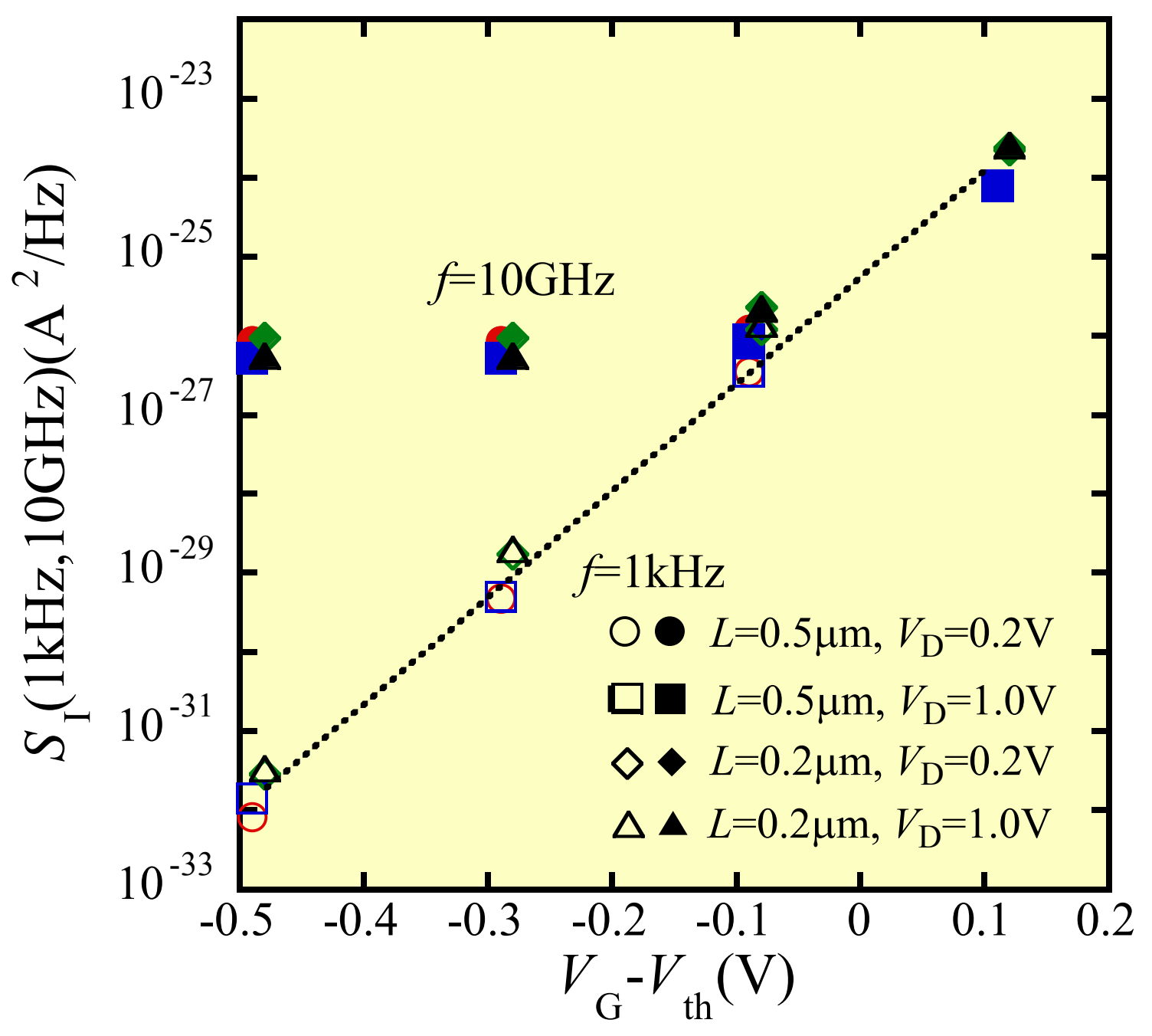
$S_I(f) \sim 2qI$ **(dotted line)**

Shot noise is constant and dominated by current.

high frequency region:

$S_I(f) \sim 8kTg(f)$ **(dashed line)**

Shot noise is frequency dependent and independent on V_D.



Estimated shot noise intensity at low-frequency (1kHz) and high-frequency (10GHz) region

Estimated shot noise is:
almost independent on V_D
increased with decreasing L

low-frequency shot noise:
exponentially enhanced by V_G
high-frequency shot noise:
independent on voltage and quite larger than low-freq. at small V_G

Summary

The shot noise generated at source-bulk interface in n-MOSFET has been estimated.

We expand shot noise model for p-n diode to be applicable for MOSFET.

Numerical simulation by 2D device simulator MEDICI shows that low-frequency shot noise is small and exponentially dependent on gate bias although high-frequency component is quite larger under small voltage.

Our results suggest that the shot noise may be serious proble at GHz or higher frequency because the noise intensity never decreases even at quite small bias condition. This should be noticed for future small-power devices.