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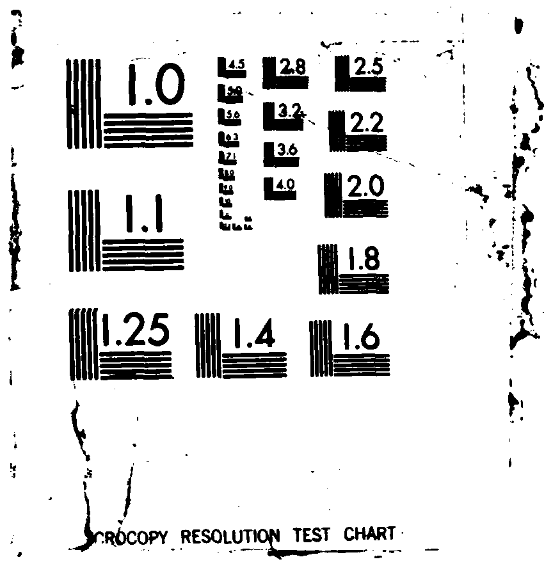
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20. Abstract

Working in the Drude approximation, the following relation is obtained for relative quantum uncertainty for current flow in micro devices,

$$\frac{\Delta J}{J} \geq \frac{1}{\bar{m}^*} \frac{\lambda\!\!\!^{-}_C}{2a} \frac{c}{v}$$

In this relation, $\lambda\!\!\!^{-}_C$ is the Compton wavelength, $\bar{m}^*$ is effective charge-carrier mass divided by electron mass, v is drift velocity, c is the speed of light and a is the channel length of the conduction domain of the device. With $v \leq c$ and at fixed $\bar{m}^*$, we see that for sufficiently small values of a, the reliability of a micro logic gate is impaired due to quantum uncertainty. Application to GaAs and InP, at present-day values of maximum charge-carrier drift velocities, reveals critical scale lengths $\approx 10^{-3}$ μm.

Introduction and Analysis

Logic gates in very large-scale integrated circuits typically employ standard variations of field-effect transistors (FET).[1,2] In micro circuits, dimensions of such devices are of the order of 1 μm. Current technology seeks to further reduce the scale-length of micro-computer networks.[3] Thus, the present work examines limitations imposed on the reliability of such logic gates due to quantum uncertainty which enters in the limit of small dimensions.[4,5]

The uncertainty relation for momentum p and displacement x is given by

$$\Delta p \Delta x \geq \frac{\hbar}{2} \tag{1}$$

Uncertainty in momentum, say, is written for the mean-square displacement from the mean,

$$(\Delta p)^2 \equiv \langle(\langle p\rangle - p)^2\rangle \tag{2}$$

With m^* denoting effective mass and v written for drift velocity we write

$$p = m^* v$$

Substitution into (1) gives

$$\Delta v \geq \frac{\hbar}{2m^* a} \tag{3}$$

where a is written for the channel length of the FET. Working in the Drude approximation,[6] we write

$$J = env \tag{4}$$

for current density, where n is charge-carrier number density and e is electronic charge. The preceding relation permits (3) to be written

$$\Delta J \geq \frac{en\hbar}{2m^* a} \tag{5}$$

Dividing through by current density gives

$$\frac{\Delta J}{J} \geq \frac{1}{\bar{m}^*} \quad \frac{\lambda_C}{2a} \quad \frac{c}{v} \tag{6}$$

where

$$\lambda_C = \frac{\hbar}{m_e c} = 3.86 \times 10^{-11}\ \text{cm},$$

is the Compton wavelength, m_e is electron mass, $\bar{m}^*$ is the dimensionless effective mass,

$$\bar{m}^* \equiv \frac{m^*}{m_e} \quad ,$$

and c is the speed of light.

The expression (6) indicates that current resolution is maintained providing the scale-length a is sufficiently large and drift velocity v is as large as feasible.

For n-type GaAs and InP, $\bar{m}^* \simeq 0.07$.[7,8] Recently measured[9,10] upper limits of v indicate $v \simeq 4 \times 10^7$ cm/s. Substituting these values in (6) gives

$$\frac{\Delta J}{J} \geq \frac{2.14 \times 10^{-7}}{a} \tag{7}$$

Conclusions

Assuming that current resolution is lost at $\Delta J/J \gtrsim 1/2$, with (7) we find that such will be the case for scale lengths $a \leq 4 \times 10^{-7}$ cm = 4×10^{-3} μm. Repeating the calculation for p-type GaAs and InP ($\bar{m}^* \simeq 0.5$), gives the limiting channel length. $a \simeq 6 \times 10^{-4}$ μm.

We have applied the quantum mechanical uncertainty relation for coordinate and momentum to obtain a relation for quantum uncertainty of current flow in micro devices. It is argued that such uncertainty, when present, would destroy the reliability of input-output relations in micro-logic gates, thereby placing a lower bound on the dimensions of such devices.

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