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Theoretical Interpretation of Field Effect Experiment of Amorphous Semiconductor

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〈Abstract〉

The field-effect-experiment data of the hydrogenated a-Si prepared by the glow discharge decomposition of silane was analyzed by the theoretical method of a-Si Field-Effect-Transister (FET) under assumption of exponential $N(E)$.

The theory predicts that log I_D−log (V_F-V_{FB}) curve becomes linear and the prediction and the experimental results are qualitatively in good agreements.

비정질 반도체의 장효과 실험의 이론적 고찰

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(1984. 4. 30. 접수)

〈요 약〉

직류 글로우 방전에 의한 사일렌의 분해로 제작된 수소화된 비정질규소에 대한 장효과 실험결과를 a-Si FEF 이론으로 해석해 보았다. 이론은 $\log I_D-\log(V-V_{FB})$의 그래프가 직선이 될것으로 예상하였는데 실험결과와 잘 일치하였다.

I. Introduction

The interpretation of the field-effect-conductance measurements in amorphous semiconductor have been the principal aid in the determination of the density of localized states, $N(E)$, in the mobility gap.[1)-3)] In this determination, we have to assume that the amorphous semiconductor is homogeneous and that the only effect of surface states is to produce a non-zero flat-band voltage (V_{FB}). Spear and LeComber[1)] used the following three assumptions in the interpretation of the field-effect data; a) parabolic (or exponential) band bending profiles, b) uniform space charge density in a certain extent (abrupt approximation) and c) zero-temperature statistics.

The removal of any one of the three approximations necessitates $N(E)$ to be found by an iterative self-consistent method.[3)-5)] Demassa et. al.[6)] and Kishida et. al.[7)] have analyzed the amorphous Si field-effect-transister (a-Si FET) characteristics under the assumption of the exponential localized states density distribution (LSDD) in the gap with respect to energy.

In this paper we present a simple equation on the characteristics of a-Si FET with realistic semiconductor film thickness having expo-

nential LSDD. And we analyze the experimental results obtained from KAIST[8] using these equations.

II. Theory

1. Analysis of MIS characteristics

We consider a metal/insulator/semiconductor (MIS) structure as illustrated in Fig. 1.

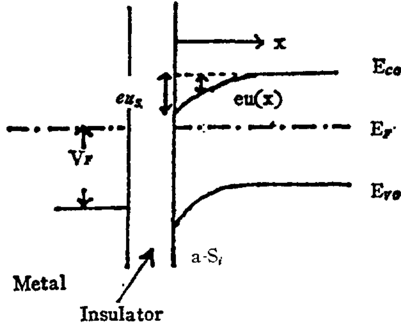

Fig. 1. An energy band diagram of MIS structure

The band bending in the space charge layer of the amorphous semiconductor defined by

$$u(x)=[E_{c0}-E_c(x)]/e \tag{1}$$

follows Poisson's eq.

$$\frac{d^2u(x)}{dx^2}=-\frac{\rho(x)}{\kappa_s\varepsilon_0} \tag{2}$$

where κ_s is a dielectric constant of amorphous semiconductor, ε_0 is the dieletric permittivity of free space and $\rho(x)$ is the local space charge density at x due to the local Fermi level shift of $eu(x)$. Let us take x-axis perpendicular to the interface.

As for a-Si, the concentration of excess electrons trapped in the localized states, n_t, is much higher than that of excess electrons induced in the conduction band, n_c, then

$$\rho(u)\simeq n_t(u) \tag{3}$$

and

$$n_t=\int_{E_{v0}-eu}^{E_{c0}-eu}N(E+eu)f(E)\,dE-\int_{E_{v0}}^{E_{c0}}N(E)\,f(E)\,dE \tag{4}$$

where E_{c0} is the bottom of the conduction band and E_{v0} is the top of the valence band under thermal equilibrium and $f(E)$ is the Fermi-Dirac distribution function.
And

$$n_c=n_0\left[\exp\left(\frac{E_{c0}-E_c}{k_BT}\right)-1\right] \tag{5}$$

where $n_0=N_{c0}\exp\left(\frac{E_F-E_{c0}}{k_BT}\right)$ under a thermal equilibrium, N_{c0} is effective density of states at $E=E_{c0}$ and E_F is Fermi level

Let us assume the exponential LSDD, i.e.

$$N(E)=N_0\exp\left(\frac{E-E_c}{k_BT_0}\right) \tag{6}$$

where N_0 is the localized states density just under the conduction band and T_0 is the characteristic temperature.

When $T_0\gg T$, where T is ambient temperature, we can use the zero-temperature statistics, then

$$n_t=\int_{E_F}^{E_F+eu}N(E)=k_BT_0N'_0\exp\left\{\frac{E_F-E_{c0}}{k_BT_0}\right\}\left[\exp\left(\frac{eu}{k_BT_0}\right)-1\right] \tag{7}$$

where N_0' is the corrected N_0 value derived in the Appendix of Ref. 7).

By the eqs. 2) and 3), Poisson's eq.

$$\frac{d^2u}{dx^2}=-\frac{en_t}{\kappa_s\varepsilon_0} \tag{8}$$

If both sides of eq. 8) are multiplied by $2du/dx$, then

$$2\frac{du}{dx}\frac{d^2u}{dx^2}=\frac{d}{dx}\left(\frac{du}{dx}\right)^2=-2\frac{e\,n}{\kappa_s\varepsilon_0}\left(\frac{du}{dx}\right) \tag{9}$$

Therefore

$$\frac{du}{dx}=-\sqrt{\int_0^x 2\frac{e\,n_t}{\kappa_s\varepsilon_0}\frac{du}{dx}dx}=-\sqrt{\int_0^{eu}2\frac{e\,n_t}{\kappa_s\varepsilon_0}du}=-\sqrt{\frac{2k^2T_0^2N_0'}{\kappa_s\varepsilon_0}\left\{\exp\frac{eu}{k_BT_0}-\frac{eu}{k_BT_0}-1\right\}\exp\left(\frac{E_F-E_{c0}}{k_BT_0}\right)} \tag{10}$$

Let N_t and N_c be the total excess electron density per unit area calculated from eqs. 3) and 4) respectively, then

$$N_t=\int_0^\infty n_t dx$$
$$=\int_0^{u_s} n_t \frac{du}{du/dx}$$
$$=\sqrt{\frac{\kappa_s\varepsilon_0 N_0'}{2}}\exp\left(\frac{E_F-E_{c0}}{2k_BT_0}\right)$$
$$\int_0^{u_s}\frac{\exp\frac{eu}{k_BT_0}-1}{\sqrt{\exp\frac{eu}{k_BT_0}-\frac{eu}{k_BT_0}-1}}du \quad 11)$$

and

$$N_c=\int_0^\infty n_c dx$$
$$=\frac{N_{c0}}{k_BT_0}\sqrt{\frac{\kappa_s\varepsilon_0}{2N_0'}}$$
$$\times\exp\left\{\frac{(2T_0-T)(E_F-E_{c0})}{2k_BTT_0}\right\}$$
$$\times\int_0^{u_s}\frac{\exp\frac{eu}{k_BT_0}-1}{\sqrt{\exp\frac{eu}{k_BT_0}-\frac{eu}{k_BT_0}-1}}du \quad 12)$$

where $u_s=u(0)$, i.e. surface potential.

When the field voltage V_F is sufficiently large,

$$eu_s \gg k_BT_0$$

is satisfied. Then N_t and N_c can be approximated by

$$N_t=\sqrt{2\kappa_s\varepsilon_0 N_0}\left(\frac{k_BT_0}{e}\right)$$
$$\exp\left\{\frac{(2T_0-T)(E_F-E_{c0}+eu_s)}{2k_BTT_0}\right\} \quad 13)$$

and

$$N_t=\frac{2T}{2T_0-T}N_{c0}\left(\frac{\kappa_s\varepsilon_0}{2N_0'e^2}\right)^{1/2}$$
$$\exp\left\{\frac{(2T_0-T)(E_F-E_{c0}+eu_s)}{2k_BTT_0}\right\} \quad 14)$$

And

$$eN_t=C_i V=\frac{\kappa_i\varepsilon_0}{d}V \quad 15)$$

where C_i is the insulator capacitance per unit area, κ_i is dielelectric constant of insulator, d is the thickness of insulator and V is defined as

$$V\equiv V_F-V_{FB} \quad 16)$$

Here V_{FB} is obtained by the method of Weisfield et. al.[9]

From eqs. 13), 14), 15) and 16), the sheet conductance σ can be written as

$$\sigma=e\mu N_c$$
$$=e\mu N_{c0}\sqrt{\frac{\kappa_s\varepsilon_0}{2T_0-T}}$$
$$\left\{\frac{\kappa_i^2\varepsilon_0}{2\kappa_s d^2 N_0' k_B^2 T_0^2}\right\}^{(2T_0/T)-1/2}$$
$$\times(V_F-V_{FB})^{(2T_0/T)-1} \quad 17)$$

and

$$u_s=\frac{k_BT_0}{e}\ln\left[\frac{\kappa_i^2\varepsilon_0}{2\kappa_s N_0' k_B^2 T_0^2}(V_F-V_{FB})^2\right]$$
$$-\left(\frac{E_F-E_{c0}}{e}\right) \quad 18)$$

2. Aanlysis of FET characteristics.

When we use the gradual channel approximation, the drain current I_D is given by

$$I_D=\sigma WF \quad 19)$$

where F is the field parallel to the interface and W is the width of a-Si. (See Fig. 2.)

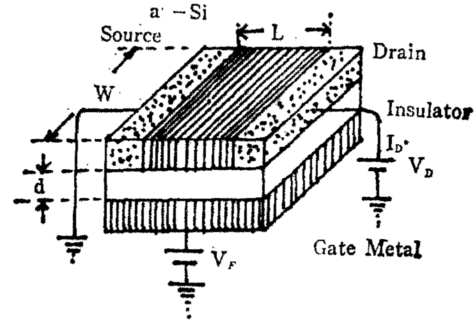

Fig. 2. Schematic diagram of a-Si FET structure

$$I_D=-\frac{W}{L}\int_{V_0}^{V_L}\sigma\,dV$$
$$=\frac{T}{2T_0}R\{V^{2T_0/T}-(V-V_D)^{2T_0/T}\} \quad 20)$$

where L is the length of a-Si, V_0 and V_L are potential at the interface and the other surface of a-Si respectively and R is the device constant defined as

$$R=\frac{W}{L}e\mu N_{c0}\frac{2T}{2T_0-T}$$

$$\sqrt{\frac{\kappa_s\varepsilon_0}{2N_0'e^2}}\left(\frac{\kappa_i^2\varepsilon_0}{2\kappa_s d^2 N_0' k_B^2 T_0^2}\right)^{(2T_0/T)-1/2} \quad 21)$$

Especially in case that the source-to-drain voltage $V_D \simeq 0$,

$$I_D = R\ V^{(2T_0/T-1)} \cdot V_D$$

$$= R\ V_D(V_F - V_{FE})^{(2T_0/T-1)} \quad 22)$$

and, if $(V_F - V_{FB} - V_D) < 0$

$$I_D = -\frac{W}{L}\int_v^0 \sigma\, dV$$

$$= \left(\frac{T}{2T_0}\right) R \cdot (V_F - V_{FB})^{2T_0/T} \quad 23)$$

From eqs. 22) and 23), we know that $\log I_D - \log(V_F - V_{FB})$ plots are straight lines.

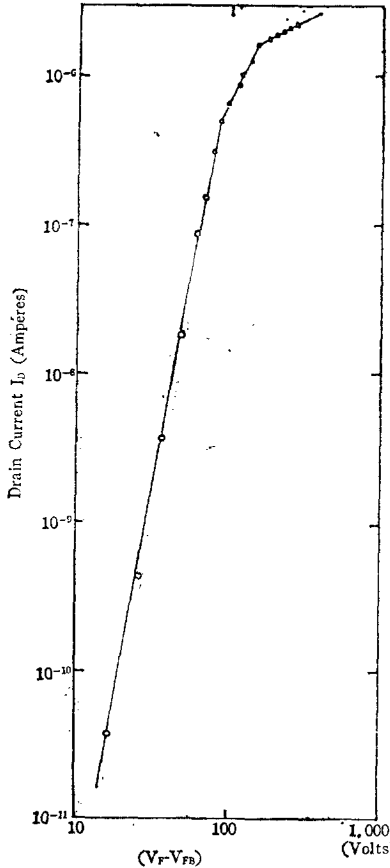

Fig. 3. $\log I_D - \log(V_F - V_{FB})$. **There are two kinks.**

III. Comparision with the experimental results and discussions.

Experimental results obtained from KAIST[6] was illurtrated in Fig. 3.

It can be see that $\log I_D - \log(V_F - V_{FB})$ data is presented by a kinked line. This kinked line means that the $N(E)$ falls off exponentially toward the midgap (for small V_F) and there are extremely high localized state density near conduction band edge. The line kinked at $V_F = 70$V and this means that the transition from low $N(E)$ near midgap to high $N(E)$ near the conduction band edge is very sharp. $T_0 = 974$K when $V_F < 70$V. But there is another kink at $V_F = 140$V. $T_0 = 338$K when $70\text{V} < V_F < 140\text{V}$.

If $V_F > 140$V, $T_0 < T$, then our analysis does not valid in this region. The method of analysis in this region will be presented near future.

IV. Conclusions.

The field-effect-experiment data of the hydrogented a-Si films prepared by glow discharge decomposotion of silane was analyzed by an FET theory. In this analysis we assume that the exponential LSDD. When $T_0 \gg T$, $\log I_D - \log(V_F - V_{FB})$ curves become linear and the line is kinked at $V_F = 70$V and 140V.

The small slope below $V_F = 70$V means that the $N(E)$ falls off exponentially with repect to energy toward the midgap and the $N(E)$ is low as compared with the region above $V_F = 70$V and 140V. The $N(E)$ near the conduction band from low $N(E)$ to high $N(E)$ is very sharp.

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