
K. Uosaki and H. Kita

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Norman Hackerman
Editor

Effects of the Helmholtz Layer Capacitance on the Potential Distribution at Semiconductor/Electrolyte Interface and the Linearity of the Mott-Schottky Plot

K. Uosaki and H. Kita
pp. 895-897, Vol. 130, No. 4

H. Gerischer: The paper of the above authors contains some serious errors in the equations quoted. The last term in the numerator of Eq. [4] must read $n_d \cdot \epsilon_0 \eta$, not $n_d$. Equations [8] and [9] represent the approximation for the case of a depletion layer in a n-type semiconductor and should read correctly

$$ Q_{sc} = \frac{(2 \varepsilon \varepsilon_0 N_d)^{1/2}}{2} \left( \frac{kT}{\epsilon_0} \right)^{1/2} $$

$$ C_{sc} = \frac{(2 \varepsilon \varepsilon_0 N_d)^{1/2}}{2} \left( \frac{kT}{\epsilon_0} \right)^{1/2} $$

Besides this, the paper gives a misleading impression of the relation between the space-charge layer capacitance and the Helmholtz double-layer capacitance of normal semiconductor electrodes since the calculations are made with an unusually high carrier concentration in the bulk ($n_d = N_0 = 10^{17}$ cm$^{-3}$) and an exceptionally large dielectric constant ($\epsilon = 173$). Most semiconductors such as ZnO, CdS, CdSe, GaP, GaAs, Si, MoS$_2$, MoSe$_2$, WSe$_2$, and WS$_2$ have static dielectric constants in the order of 6-12. Usual carrier concentrations are in the order of $10^{16}-10^{18}$. With such values, the space-charge capacitance is by far smaller than for the example given in this paper. Consequently, the relation between the variation of the voltage drop in the Helmholtz double layer and the voltage applied to the whole interface (referred to the flatband potential) is drastically reduced in comparison to the data given in Fig. 1 of this paper.

More realistic data are shown in Fig. 1a and b, which was derived for depletion layers in the absence of surface states from the following relations, being valid for $n_d > 4$

$$ Q_{sc} = \frac{(2 \varepsilon \varepsilon_0 N_d)^{1/2}}{2} \left( \frac{kT}{\epsilon_0} \right)^{1/2} $$

$$ C_{sc} = \frac{(2 \varepsilon \varepsilon_0 N_d)^{1/2}}{2} \left( \frac{kT}{\epsilon_0} \right)^{1/2} $$

$$ y_{sc} = \frac{e \Delta \psi_{sc}}{kT} \quad \text{with} \quad \Delta \psi_{sc} = \psi_f - \psi_0 $$

$$ y_{H} = \frac{e \Delta \psi_{H}}{kT} = 2 C_{sc} \left( \frac{y_{sc} - 1}{2} \right) $$

The voltage drop in the space-charge layer $\Delta \psi_{sc}$ and in the Helmholtz layer $\Delta \psi_{H}$ is represented in Eq. [3] and [4] in terms of $kT/e$ units (25 mV at $T = 298$ K). With $\varepsilon_0 = 8.854 \times 10^{-12}$ A s V$^{-1} \cdot$ cm and $C_{H} = 10 \mu F$, the relation $\Delta \psi_{sc}$ has been calculated and is plotted against $y_{H}$ + $y_{sc}$ in Fig. 1a for $N_0 = 10^{19}$ and $10^{17}$ with $\epsilon = 173$, and in Fig. 1b for the same donor concentrations with $\epsilon = 10$. One sees that the relative contribution of $y_{H}$ to the whole potential drop $y_{H}$ + $y_{sc}$ is very small for $N_0 = 10^{19}$ and $\epsilon = 10$, representing the usual situation in semiconductor electrochemistry.

The necessary correction for the variation of $\Delta \psi_{H}$ in the extrapolation to the flatband potential in a Mott-Schottky plot is correctly derived in the paper of DeGrose et al. and quoted as Eq. [10] in the above paper. It is, however, also drastically reduced, if the dielectric constant has a normal value and the donor density is

$$ y_{H} = \frac{e \Delta \psi_{H}}{kT} = 2 C_{sc} \left( \frac{y_{sc} - 1}{2} \right) $$

$^1$R. De Gryse, W. P. Gomes, F. Cordon, and J. Vennik, This Journal, 123, 711 (1975).
smaller than 10$^9$. De Gryse et al. have found with $C_0 = 10$ $\mu$F as correction for the extrapolated value of $V_{E_0}$ at a n-type semiconductor with $\epsilon = 173$ and $N_n = 10^{19}$ the large value of $-0.12$V. From the correction formula, $\delta V = -[eE_n/(2C_0)],$ one obtains with $\epsilon = 10$, instead of 173, only $-7$ mV, and with $N_n = 10^{19}$ instead of $10^9$, this correction is fully negligible.

It is certainly important to be aware of the possibility that the potential drop in the Helmholtz double layer can vary with the applied voltage. However, one should also see that the importance of the variance of this effect depends very critically on the doping level and the magnitude of the dielectric constant. A variation in $\Delta\phi$ will much more often be due to the presence of surface states with a density in the order of $10^{19}$ cm$^{-2}$ within a narrow range of energies.

K. Uosaki and H. Kita: We must admit that Eq. [4], [8], and [9] of our paper contain misprints, as Professor Gerischer has pointed out. But note all the calculations have been carried out by using proper equations.

Although Gerischer commented that our calculations were made only with an unusually high carrier concentration in the bulk ($n_0 = N_n = 10^{19}$ cm$^{-2}$), we calculated the potential distribution with a wide range of carrier concentrations ($10^{18}$ cm$^{-2}$ $\sim 10^{19}$ cm$^{-2}$) as shown in Fig. 1 of our paper.

Gerischer said this paper gives a misleading impression of the relation between the space-charge layer capacitance and the Helmholtz double-layer capacitance of normal semiconductors. However, we think it is important to stress the effects of the Helmholtz double-layer capacitance on the potential distribution and linearity of the Mott-Schottky plot because many semiconductor electrochemists simply ignore the Helmholtz layer capacitance without considering its physical significance.

As far as the effect of the Helmholtz layer capacitance on the linearity of the Mott-Schottky plot is concerned, we support the general conclusions of De Gryse et al. but pointed out that the real Mott-Schottky plot deviates from the linear line calculated by using Eq. [10] of our paper, which was derived by De Gryse et al. with the Mott-Schottky approximation, near the flatband potential.

**Galvanostaircase Polarization**

S. T. Hirozawa

pp. 1718-1721, Vol. 130, No. 8

F. Mansfeld: Hirozawa's paper gives an interesting application of a very simple experimental technique. However, some discussion of the conclusions by the author concerning pitting of aluminum is necessary to avoid even more confusion in the general topic of "critical potentials" than there exists now. There is no theoretical justification in this paper for the claim that extrapolation of the E-I curves to $I = 0$ leads to the breakdown potential $E_b$ for increasing $I$ and to the protection potential $E_{prot}$ for decreasing $I$. The statement "E appears to have no direct relevance to localized corrosion because E does not have to be raised above $E_{in}$ to initiate pitting; one only needs to raise E above $E_{prot}$ to initiate pitting. Hence, $E_b$ is not a critical potential, but it does have indirect relevance because the greater the difference between $E_{prot}$ and $E_b$, the greater is the tendency for crevice corrosion." Mansfeld's statement that "in analyzing Hirozawa's experiment, one could conclude that the application of the first current step produces pitting" is true for Fig. 3 and 4, where the evidence for pitting is quite apparent. Pitting occurs on metals that are passivated, preferably by a layer of insoluble salts. In Fig. 1 and 2, pitting is not evident. Chloride is nonpassivating; therefore, the corrosion is general and not localized. The passivation of Al by nitrate is unique. The first current step does not break down the passive layer, but rather it builds it up further. Hence, the use of the term, $E_b$, is not appropriate; it is used here for the want of a better name. The gradual change of potential during the first two steps probably indicates changes in the resistance of the inner oxide layer as well as the distribution of nitrate within the passive layer under the influence of the electric field.

In conclusion, the GSCP method should dispel some of the confusion related to the critical potentials, induction effects, and the scan rate, hysteresis, and charge effects on the value of $E_{prot}$.

**The Effect of Stress on the Redistribution of Implanted Impurities in GaAs**

J. Kasahara, Y. Kato, M. Arai, and N. Watonobe

pp. 2275-2279, Vol. 130, No. 11

C. Blaauw: The authors analyze the effect of stress, induced by a plasma silicon nitride capping film, on the diffusion constants for Si and Se implants in GaAs. Several incorrect assumptions are made, which affect analysis of the results. For example, Eq. [1] implies that the influence of stress on the capping film is taken to be zero, whereas it is well known that plasma silicon nitride films...
are deposited in a state of tensile stress (11, 12). More seriously, the analysis of the diffusion coefficients in terms of jump frequency and vacancy concentration rests on the assumption that the substrate-induced stress at 850°C is proportional to the thickness of the capping film. This assumption is not justified, as the properties of plasma silicon nitride are not necessarily uniform throughout the film. We have carried out stress measurements as a function of film thickness, for plasma silicon nitride on GaAs, which show that both the intrinsic stress and the temperature dependence of the stress depend on film thickness (2). Extrapolating stress vs. temperature curves to 850°C, we find that the substrate-induced stress for a 0.4 μm film is only approximately 40% larger than that of a 0.1 μm film deposited under the same conditions. If a similar relationship were to apply for the work under discussion, this would move the data points at ~0.3 μm in Fig. 7, of the paper in question well to the left on the corresponding stress scale, in good agreement with the linear solid line of this figure. This would imply that there is no need to assume a stress-dependent vacancy concentration within the region of investigation.

J. Kasahara: I appreciate the interest and useful reading of our paper.

Basically, I agree with the comments, which pertain mainly to our Fig. 7. Although further quantitative study is necessary, if the intrinsic stress and thickness-dependent temperature dependence of the stress have some influence, the scale of the lower axis for the stress might be modified. Dr. Blaauw discussed this subject in his Ref. (2), which was not available when our manuscript was being prepared. Also, it is difficult to apply his data directly to our data, because the deposition system for SiN is different. Further, considering the behavior of the stress dependence of the diffusion of Zn, known to be by an interstitial-substitutional mechanism, and the result of Se with about 0.6 μm of thicker SiN, I think it is too important to ignore the effect of the vacancy concentration. Further discussion probably requires measuring the stress in situ at the annealing temperature investigated.

3Sony Corporation Research Center, Yokohama 240, Japan.