In addition to adsorption of H⁺ and OH⁻ ions at the ZnO/aqueous solution interface a slow H⁺ or OH⁻ consuming process has been observed. Although the amount of H⁺ or OH⁻ consumed by this process is approximately proportional to the square root of the time, a diffusion-controlled process is excluded. All phenomena observed can be accounted for by the following mechanism: At pH < 8.9, H⁺ ions react with surface hydroxyl groups, but, after an initial stage, this reaction can proceed only if a free electron is available at or near the reacting group. Similarly, at pH > 8.9, OH⁻ ions react with $\equiv$ZnOH groups, but this reaction is, after an initial stage, confined to groups which have a hole (a vacant state in the valency band) in their vicinity. This causes the reaction rate of the slow process to be governed by the development of a space charge in the solid.

INTRODUCTION

Recently (1) an investigation was reported on the discrepancies existing in the literature (2) between the double-layer capacities at the ZnO/aqueous electrolyte solution interface as obtained by three different methods: (a) The theoretical, Gouy–Chapman capacity of the diffuse double layer; (b) the capacity as measured in titration experiments; and (c) the capacity as measured in an ac bridge.

As the main cause for these discrepancies, the lack of taking into account a "slow" process, consuming H⁺ or H⁻ ions, was held responsible. This process is superimposed on the adsorption of these ions at the ZnO surface: by extrapolating the slow process to time = zero, capacities were obtained which agree well both with theoretical capacities and (at the pzc) with capacities measured at AgI/aqueous solution interfaces (3). Obviously a reliable extrapolation of the slow process requires knowledge of its mechanism. The present paper reports additional experiments, performed in order to elucidate this mechanism.

EXPERIMENTAL

Materials

The same materials were employed as described previously (1). ZnO single crystals were obtained from Prof. Heiland, Technische Hochschule Aachen, West Germany; they had been grown from the vapor phase. Double-tracered $^{24}$Na$^{82}$Br was obtained as described earlier (4).

Apparatus

H⁺ and OH⁻ consumption by the ZnO was studied as described previously (1). Electrophoresis was carried out in a cell according to Smith and Lisse (5) using platinized Pt electrodes. $^{24}$Na$^{82}$Br adsorp-
Fig. 1. [OH⁻−H⁺] consumption by ZnO in 0.1 M NaCl solution at pH = 8. (A) Influence of light: (a) in the dark; (b) unprotected against light. (B) Comparison with theory: (a) \( \sigma = At^{1/2} \); (b) according to relation [7] (after integration).

**Procedure**

(1) Electrophoresis: During the experiments on H⁺ or OH⁻ consumption by a ZnO suspension as a function of time at constant pH (1), at predetermined times 25 ml was pipetted from the suspension. This sample was immediately filtered with suction in an atmosphere of purified nitrogen (about 2 min). To the clear filtrate, 50 µl of the original suspension was added, and the resulting suspension was introduced into the electrophoresis cell. Electrophoretic mobilities were converted into \( \zeta \)-potentials using the method of Wiersema et al. (6), taking into account the mobilities of Na⁺ and Cl⁻ (\( m_+ = 45.6 \text{Ω} \cdot \text{cm}^2 \text{eq}^{-1} \) and \( m_- = 68.4 \text{Ω} \cdot \text{cm}^2 \text{eq}^{-1} \)). In these calculations the radius of the ZnO particles was taken as the radius of a sphere of specific surface equal to that of the ZnO sample.

(2) \(^{24}\text{Na}^{82}\text{Br}\) adsorption was investigated by the same method as described earlier (4) at pH 7.7 and 10.6. The pH was kept constant by means of titration equipment similar to that used for the suspension measurements (1). After contact with the \(^{24}\text{Na}^{82}\text{Br}\) solution for 4 hr, the single crystal was washed seven times with untraced NaBr solution, and then etched in 0.01 M HCl. No difference with etching in HClO₄ instead of HCl was noticed.

**RESULTS**

An overall view of the H⁺ and OH⁻ consumption at constant pH as a function of time has been presented in the preceding paper (1). One experiment is described with additional information (see later) in Fig. 1A and another one in Fig. 2A. Negative \( \zeta \)-potentials were observed throughout (Fig. 3), even in the suspension at pH 8.0 after 4000 min reaction, when the ZnO has consumed a net amount of H⁺. By reason of charge balance, an additional amount of Cl⁻ must have been transferred behind the electrokinetic slipping plane.

In fact, the \( \zeta \)-potentials observed are practically independent of the reaction time (Fig. 3). The general course of the \( \zeta \)-potentials as a function of pH agrees well with Healy and Jellet's data (7).

At all pH values investigated the "slow" reaction can be described approximately (1) by the equation

\[
\sigma = At^{1/2}
\]

with \( \sigma \) = the amount of H⁺ and OH⁻ consumed by the slow process up to time \( t \).

Figure 4 shows the coefficient \( A \) observed as a function of pH; a positive value corresponds with H⁺ consumption, a negative one with OH⁻ consumption. Values of \( A \) were determined by least-squares analysis...
of the data; values obtained at [NaCl] = 0.001 M are more uncertain because it was more difficult in these solutions to keep the pH constant as compared with 0.1 and 0.01 M solutions.

In Figs. 1A and 2A, two experiments are shown: one (a) in a reaction vessel shielded against light influence, the other (b) not protected against light. The latter curve shows the diurnal rhythm of light and dark: light enhances OH\(^-\) consumption and counteracts H\(^+\) consumption. This effect was, to the accuracy obtained, independent of the pH and no sign of saturation was found during a 3 day and night experiment.

Figures 5 and 6 show the results of \(^{24}\)Na\(^+\) and \(^{82}\)Br\(^-\) adsorption experiments. It is seen that at pH 7.7, Br\(^-\) is preferentially adsorbed (which is seen in the bending off of the Br\(^-\) activity curve from a straight line during the later washings) and that even after 4 hr contact with NaBr solution Br\(^-\) ions have penetrated far into the ZnO (about 7000 Å). At pH 10.6 similar data hold for the Na\(^+\) ions. Penetration of such ions, however, can for sterical reasons be expected only at dislocations.

**DISCUSSION**

Any mechanism for the slow reaction must be compatible with the following conditions:

1. The kinetics of the process can be approximated between 1200 and 4000 min by a relation of the type \(\sigma = At^{1/2}\).
2. The proportionality constant \(A\) depends on the pH.
3. \(A\) does not depend on the NaCl concentration.
4. \(A\) shows a smooth transition, without a break in the slope, from positive to negative values near the pzc (pH 8.7); and at equal distances from pH 8.9, the absolute values of \(A\) are about equal.
5. The \(\zeta\)-potential is <0 and independent of the time.
6. Light stimulates OH\(^-\) consumption and counteracts H\(^+\) consumption.
7. At pH < 8.9, Br\(^-\) ions from NaBr solution (presumably also Cl\(^-\) in NaCl solution) penetrate deep into the ZnO; at pH > 8.9 the same obtains for Na\(^+\) ions.

A $t^{1/2}$ proportionality often indicates a diffusion-controlled process; thus we checked this possibility carefully. Since the suspension was intensively stirred, concentration gradients in the liquid phase may be excluded. Moreover, conditions in the liquid medium remain constant with time except for a small increase in electrolyte...
concentration due to the addition of NaOH or HCl to keep the pH constant. Diffusing species in the solid might be H⁺ at pH < 8.9 and OH⁻ at pH > 8.9. To be sure, H⁺ ions should have a much higher diffusivity in ZnO than OH⁻ which would lead to a contradiction with condition 4. This, however, might be circumvented by postulating OH groups in the bulk of the initial ZnO at point defects; at pH > 8.9, the protons of such groups could diffuse out of the ZnO. Diffusion of protons into Fe₂O₃ has been assumed by Onoda and de Bruyn (8). The objection that an accumulation of charge in the solid by such a process would be at variance with condition 5, might be answered by assuming simultaneous transfer of counterions (Cl⁻ or Na⁺ at pH smaller or larger than 8.9, respectively) to the region behind the electrokinetic slipping plane. However, such a diffusion is influenced by the electric potential generated, such as to superimpose a drift current upon a diffusion current (9):

\[ J_{H^+} = -D \text{ grad } [H^+] - [H^+] \times \frac{e_0 D}{kT} \text{ grad } \psi \]  

where

- \( D \) = the diffusion constant of protons in \( \text{ZnO} \);
- \( e_0 \) = the charge of the proton;
- \( \psi \) = the local electrical potential;
- \( J_{H^+} \) = the flux of \( H^+ \) ions.

A \( t^{1/2} \) proportionality is obtained only if the second term is negligible compared with
the first over the entire period during which this relation is observed. If the counterions remain outside the solid (or penetrate the solid only at dislocations), whereas H⁺ diffuse into and out of undisturbed regions of ZnO, we know grad ψ at the boundaries of these undisturbed regions: by Poisson’s relation, for a flat surface

\[ \frac{d\psi}{dx} = -\int_0^\infty \frac{\rho}{\epsilon_0 \epsilon} dx = -\frac{\sigma}{\epsilon \epsilon_0} \]  

with

- \( \rho \) = space charge density;
- \( x \) = distance from the surface, regarded as positive in the direction into the solid;
- \( \epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1} \);
- \( \epsilon_r \) = the dielectric constant of ZnO (≈8.5 (10)), regarded as independent of \( x \).

In the present context, this relation is applied in the solid. \( \sigma \) is then the total charge per unit surface in the solid if \( d\psi/dx \) is attached its value just behind the phase boundary, but still within the solid.

Thus, after 3800 min at pH 8, where the \( t^{1/2} \) relationship is still obeyed, grad \( \psi \) would become \( \approx 1 \times 10^8 \text{ V m}^{-1} \), and if diffusion of protons is rate determining, \( d \ln [\text{H}^+] / dx \) in the solid must be large compared with \( 4 \times 10^{10} \text{ m}^{-1} \). This, however, would mean that the proton concentration in ZnO decreases to \( 1/e \) of its surface concentration well within one unit cell, which excludes a diffusion controlled process.

In view of the order of magnitude of \( \text{grad } \epsilon_0 \psi / kT \), the consideration that the double layer near a dislocation is not really flat does not impair our conclusion.

Simultaneous diffusion of equimolar quantities of H⁺ and Cl⁻ into the ZnO at pH < 8.9, or exchange of Na⁺ against H⁺ at pH > 8.9, would remove this discrepancy. In order to be sterically possible, such a process should be restricted to dislocations. However, this mechanism is incompatible with conditions 3 and 4. Moreover, it does not obviously explain condition 6. A mechanism which is consistent with all conditions mentioned is the following:

At the first contact of ZnO with an aqueous solution, adsorption of H⁺ and OH⁻ occurs (indicated as “primary adsorption”). This is saturated at a relatively low degree of surface coverage. In addition, a reaction of surface \( \equiv \text{Zn} – \text{OH} \) groups takes place with H⁺ ions at pH < 8.9, with OH⁻ ions at pH > 8.9; the rate of this reaction is proportional to the concentrations of free electrons or holes (vacant states in the valency band), respectively, at the surface. The charge, transferred by this process to the solid, does not remain at the surface itself but is distributed by electron transport, over the near surface region of the solid, forming a depletion layer or counter-acting an accumulation layer at pH < 8.9, forming or enhancing an accumulation layer at pH > 8.9 (see Fig. 7). In Fig. 7 only the charges due to the slow process are indicated; in addition, surface charges are generated by primary adsorption and by chemisorption of Cl⁻.

This mechanism is consistent with conditions 2, 3, and 5, and also with the anti-symmetrical character of the reaction rate with respect to the pzc (condition 4), since it does not involve transport of Na⁺ or Cl⁻ ions in the solid (except in dislocations,
and then not as a rate-determining step. Consistency with condition 1 can be obtained as follows: Proportionality of the reaction rate with the free electron concentration near the surface requires a proportionality with $\exp(Y_s)$ (where $Y_s = e_0\psi_{\text{solid}}/kT$, $\psi_{\text{solid}}$ = the potential difference between the surface and the bulk solid, and $-e_0\psi_{\text{solid}}$ is called "band bending" by solid state chemists (11)). Similarly, proportionality with the hole concentration requires a proportionality with $\exp(-Y_s)$. The sign of $Y_s$ is chosen in agreement with solid state usage, taking the potential in the bulk solid as zero. $dy/dx$ at the surface is known from the experimental data through relation [3], insofar as it is due to the slow process (in other words, $(dy/dx)_{x=0}$ is divided into a part due to primary adsorption and chemisorption of $\text{Cl}^-$ and a part due to the slow process; the additivity of both parts of $(dy/dx)_{x=0}$ follows from the additivity of the charges $\sigma$ transferred to the solid by the corresponding processes, cf. [3]). According to Dewald (12) for a flat space charge in an $n$-type semiconductor,

$$\frac{dy}{dx} = \frac{2e_0^2 N_D}{(e_0 kT)} \left\{ \left( \text{fe}^{y_s} - f - y_s \right) + \ln \left[ f + (1 - f)e^y \right] \right\}^{1/2}$$

with

$$N_D = \text{donor concentration in the ZnO,}$$

$$f = \text{degree of dissociation of these donors in the bulk ZnO.}$$

The minus sign is for $y_s > 0$ and the + sign is for $y_s < 0$.

Thus, for the slow process by reason of the additivity of the two contributions to $(dy/dx)_{x=0}$:

$$\left( \frac{dy}{dx} \right)_{x=0} = \frac{2e_0^2 N_D}{(e_0 kT)} \left\{ \left( \text{fe}^{y_s} - f - y_s \right) + \ln \left[ f + (1 - f)e^y \right] \right\}^{1/2}$$

$\sigma$ = charge transferred to the solid by the slow reaction at any time can be calculated. In order to do this, we write:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dy_s} \frac{dy_s}{dt}$$

where $\sigma = A(t)^{1/2}$, and this latter quantity should be proportional to $e^{y_s}$ or $e^{-y_s}$, respectively).

Table I presents some data, calculated for $f = 0.5$ and $N_D = 10^{25}$ m$^{-3}$. Other values for $f$ and $N_D$ will lead to different $y_0$ values; however, the $\sigma(t)$ curves calculated from the different sets of parameters (see below) differ from each other only to extents negligible in comparison with the experimental accuracy of the data.

From relation [5], the charge transferred to the solid by the slow reaction at any time can be calculated. In order to do this, we write:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dy_s} \frac{dy_s}{dt} = Be^{y_s}$$

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$$\frac{d\sigma}{dt} = \frac{d\sigma}{dy_s} \frac{dy_s}{dt} = Be^{y_s}$$

Here $B$ can be calculated from $d\sigma/dt$ at one particular time (say 1200 min), at which $y_s$ is known from the fitting procedure. Thus:

$$\frac{d\sigma}{dy_s} \frac{dy_s}{dt} = Be^{y_s}$$

where $y_0$ is the reduced surface potential in the solid due to primary adsorption and chemisorption of $\text{Cl}^-$ ions.

At chosen values of $f$ and $N_D$, $y_0$ can be adjusted such as to let $(dy/dx)_{x=0}$ due to the slow process approximate, say at $1200$ min $< t < 4000$ min, to a $t^{1/2}$ proportionality (which means that, at $\text{pH} < 8.9$, $e^{-y_s t^{1/2}}$ must be nearly independent of time; at $\text{pH} > 8.9$ $e^{-y_s t^{1/2}}$ must be nearly independent of time; since $\sigma = At^{1/2}$ requires $d\sigma/dt = A/(2t^{1/2})$, and this latter quantity should be proportional to $e^{y_s}$ or $e^{-y_s}$, respectively).

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dy_s} \frac{dy_s}{dt} = Be^{y_s}$$

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Here the minus sign refers to pH < 8.9 and the plus sign to pH > 8.9.

By integrating [7] from $y_s$ at 1200 min to a value $y's$, the time at which $y's$ is valid can be calculated. By combining the result [3] and [5], $\sigma(t)$ is evaluated.

The Figs. 1 and 2 compare the $\sigma(t)$ thus calculated with the experimental data and with $\sigma = At^{1/2}$. The "space charge" mechanism is seen to describe the experimental data over a more extended time period than the $t^{1/2}$ relation.

From the calculations, a value for $y_s'$ and for $\sigma$ at $t = 0$ are found. At that time, $y's$ differs from $y_0$, because the $\sigma(t)$ calculations are based on the assumption that primary adsorption and chemisorption, giving $y_0$ its value as required for the description of the slow process, proceed instantaneously.

In reality, these processes require some time, and the kinetics of the slow reaction cannot be expected to follow the calculated $\sigma(t)$ relation from $t = 0$ on, but only after some time during which changes in $y_s$ are caused not only by the slow reaction, but by the other reactions as well.

The charge $\omega_0$ transferred at any pH by primary adsorption and chemisorption to the ZnO can be calculated from $y_0$. The values are plotted, as a function of pH, in Fig. 8. They are negative at all pH values, since all $y_0$ values are positive (see Table I). This can be understood by the following mechanisms:

(a) At pH < 8.9: On the first contact of

\[
\begin{align*}
\frac{dt}{B} = \frac{e^{-\nu_s} dy_s}{d\sigma} = \frac{1}{2} \frac{e^{-\nu_s} fe^\nu_s - 1 + (e^\nu_s - fe^\nu_s)/(f + e^\nu_s - fe^\nu_s)}{2(fe^\nu_s - f - y_s + \ln [f + e^\nu_s - fe^\nu_s])^{1/2}} dy_s. 
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(a) At pH < 8.9: On the first contact of
ZnO with the aqueous solution, adsorption of H⁺ on \(\equiv\text{ZnOH}\) groups and chemisorption of Cl⁻ on \(\equiv\text{Zn}\) ions near the surface take place. Of the charges transferred to the ZnO by these processes, the negative charges imparted by Cl⁻ chemisorption are mobile (ZnO is an electronic semiconductor) and distribute themselves over the surface region (Fig. 9A).

(b) At \(\text{pH} > 8.9\): On the first contact with ZnO with the aqueous solution, \(\equiv\text{ZnOH}\) groups combine with OH⁻ ions forming \(\equiv\text{ZnO}^-\); again the negative charge imparted by this process to the ZnO forms a space charge region (Fig. 9B).

In terms of solid state chemistry, \(\equiv\text{ZnC}^-\) and \(\equiv\text{ZnO}^-\) groups form surface states whose energy levels should be situated as depicted in Fig. 10 at A and B, respectively. As far as the present authors are aware, no independent data are available about the energy levels of such states at the ZnO/aqueous solution interface; the most direct indication is the value of 1.1–1.7 eV for \(\Delta E\) (see Fig. 10) for a surface state connected with adsorbed Cl⁻ ions at the interface ZnO/dilute gas (13). The level of a \(\equiv\text{Zn—O}^-\) group may be supposed to be well above \(E_v\) (cf. Ref. (14)). Both data are quite well compatible with a situation of levels A and B above the Fermi level \(E_f\), as is necessary in order to enable the surface states concerned to yield an electron as required by the positive \(Y_0\) values found.

Thus, in all cases an accumulation layer is formed at the surface of the ZnO, and in spite of the free electrons at \(\text{pH} < 8.9\) at the surface being consumed by the reaction with H⁺, there remains an accumulation layer throughout the period investigated. The process, depicted schematically in Fig. 7A, is thus superimposed on an accumulation layer caused by chemisorption of Cl⁻.

This conclusion is supported by two experimental facts:

(a) The net negative charge behind the electrokinetic slipping plane even at \(\text{pH} < \text{pH}_{\text{zc}}\) (Fig. 3);

(b) The influence of light (Figs. 1A and 2A): light stimulates the dissociation of donors in ZnO, forming additional free electrons and holes; however, since the product of the free electron and hole concentrations must remain constant (15), the surplus electrons have to be carried away from the surface and therefore in a ZnO with an accumulation layer the surface electron concentration will be reduced by light, whereas the surface hole concentration is increased.

The surface charge due to the slow process calculated from \(Y_0\) and \(y_n\) at \(t = 1200\)
min by relation [5], can be added to the amount of OH\(^{-}\) consumed by the ZnO up to that time to give a surface charge due to both primary adsorption of H\(^{+}\) and OH\(^{-}\) and chemisorption of Cl\(^{-}\). This surface charge is referred to an arbitrary initial charge present on the ZnO as added.

In this way, the same value for \(\sigma_0\) is found as by extrapolating the \(\sigma = At^{1/2}\) relation to \(t = 0\) (see Ref. (1), Fig. 2). On the other hand a value of the total charge in the space charge layer in a situation where the reduced surface potential in the solid is \(y_0(\omega_0)\) can be calculated from relation [4] (see Fig. 8). The trend of \(\sigma_0\) as a function of pH differs, especially at pH < 8.9, from that of \(\omega_0\). This difference is attributed to chemisorption of Cl\(^{-}\). The maximum surface charge \(\omega_0 (0.18 \times 10^{-6} \text{ C cm}^{-2})\) corresponds to about 1% of a monolayer of Cl\(^{-}\), thus the charge due to primary adsorption of Cl\(^{-}\) can easily be accommodated in a monolayer.

The \(\sigma_0\) values calculated by this extrapolation method are subject to some uncertainty, insofar as the period at the beginning during which primary adsorption, chemisorption of anions, and the slow process take place simultaneously cannot be elucidated on the basis of the data available at present. In this respect measurements of the chemisorption of anions might prove helpful.

It may be surprising that \(y_0\) is relatively large in the vicinity of the pzc. However, it should be borne in mind that \(y_0\) refers to a potential gradient in the solid, whereas the pzc refers to the condition that equal amounts of potential determining ions (H\(^{+}\) and OH\(^{-}\)) are taken up by the solid. The latter condition is easily compatible with a nonzero value of \(y_0\).

CONCLUSION

The data available on the slow consumption of H\(^{+}\) and OH\(^{-}\) ions by ZnO can be explained by a mechanism comprising reactions with surface \(\equiv\text{ZnOH}\) groups with a free electron or hole, respectively.

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