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Fermi-level-dependent mobility-lifetime product in *a*-Si:H

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We have measured the gate-voltage (i.e., dark-Fermi-level) dependence of the mobility-lifetime ($\mu\tau$) product using a thin-film transistor sample, to understand the reason for the large discrepancy in $\mu\tau$ for *a*-Si:H obtained from coplanar-photoconductivity and from charge-collection or junction-recovery measurements. The $\mu\tau$ product decreased with decreasing gate voltage, and was estimated to be in the $(2-9)\times10^{-8}$ cm^2/V range in the limit of full depletion. This estimated value is in good agreement with the electron $\mu\tau$ product for our undoped *a*-Si:H (2×10^{-8} cm^2/V) from the steady-state primary-photocurrent measurement previously performed. Our result indicates that the discrepancy associated with the $\mu\tau$ product is primarily due to the difference in the position of the dark Fermi level in the two kinds of measurements.

Evaluation of the mobility-lifetime product ($\mu\tau$) is of great importance in the basic characterization of hydrogenated amorphous silicon (*a*-Si:H) films. However, there is a controversy in the evaluation of $\mu\tau$. The $\mu\tau$ values estimated from steady-state secondary-photoconductivity (SS-SPC) measurements[1,2] are generally much larger than those from time-of-flight, [charge-collection (CC)][3,4] or junction-recovery (JR) techniques;[5] the $\mu\tau$ values from the former are in the 10^{-7}–10^{-4} cm^2/V range while those from the latter are in the 10^{-9}–10^{-7} cm^2/V range. Schiff discussed this discrepancy on the basis of transient drift mobility $\mu_d(t)$, and theoretically deduced that both are equivalent but integration times are different;[6] the τ in the SS-SPC measurement is the recombination time τ_R whereas that in the CC measurement is the deep-trapping time τ_T, and τ_R is much larger than τ_T. However, this problem is not yet fully understood.

In this Communication we will present this problem from another point of view, i.e., Fermi-level E_F dependence of $\mu\tau$. We first point out problems inherent in deriving $\mu\tau$ from the SS-SPC measurement, and suggest that the $\mu\tau$ of a coplanar sample whose recombination is truly monomolecular coincides with that from the CC or JR measurements. To ensure this hypothesis, we measured the E_F dependence of photocurrent J_{ph} and the excitation intensity G dependence ($J_{ph}\propto G^{\gamma}$) of a thin-film transistor (TFT) sample by changing the gate voltage V_G, and found that $\mu\tau$ approaches what was previously obtained by steady-state primary-photocurrent (SS-PPC) measurement.[7]

The SS-SPC measurements where Ohmic coplanar electrodes are used are widely applied for the characterization of *a*-Si:H films. First we would like to point out problems inherent in the derivation of $\mu\tau$ from the measurement. One usually calculates $\mu\tau$ products from the photocurrent J_{ph} using the following equations:

$$J_{ph}=en\mu E, \tag{1}$$

$$n=G\tau, \tag{2}$$

$$G=\eta F[1-\exp(-\alpha d)](1-R)/d, \tag{3}$$

where e is the electron charge, G is the photocarrier generation rate, E is the electric field, η is the quantum efficiency usually assumed to be unity, F is the photon flux, α is the absorption coefficient, d is the film thickness, and R is the reflectance. If the recombination kinetics is monomolecular, Eqs. (1)–(3) are straightforward. However, it should be noted that, generally, G and τ are not independent variables but are dependent on each other for *a*-Si:H. This situation arises because Eq. (2) is the definition of the lifetime for a particular G. Therefore the $\mu\tau$ from the SS-SPC measurement is essentially dependent on G, and consequently, it is meaningless to compare $\mu\tau$ values of different samples measured under different Gs. The controversy in connection with the $\mu\tau$ products arises partly from this fact. The dependence of τ on G for undoped *a*-Si:H films was experimentally derived by Wronski and Daniel as[8]

$$\tau\propto G^{-(1-\gamma)}, \tag{4}$$

where γ is a constant between 0.5 and 1. This will be discussed further. Equation (4) reduces to the well-known dependence of J_{ph} on G:

$$J_{ph}\propto G^{\gamma}. \tag{5}$$

The dominant recombination kinetics of *a*-Si:H characterized by these equations have been discussed by a number of authors but are still controversial. Equation (4) indicates that τ decreases with increasing G. Its physical meaning is that the density of recombination centers increases with increasing G. To explain this, the quasitrap Fermi level for electrons and holes E_{tn} and E_{tp} have been defined so that continuous gap states in the energy region E_{tn}-E_{tp} act as recombination centers and states, in the other regions E_C-E_{tn} and E_{tp}-E_V simply act as traps.[9] Also, E_{tn}-E_{tp} increases with increased excitation intensity if a constant capture cross section is assumed. The first model for the sublinear dependence of J_{ph} on G [Eq. (5)] was presented by Rose.[10] According to the model, γ is given by

$$\gamma=T_0/(T+T_0), \tag{6}$$

where T_0 is the characteristic temperature when an ex-

ponential distribution of the conduction-band (CB) tail states, $N(E)=N_C\exp[-(E_C-E)/kT_0]$ [$N(E)$, the density-of-states at an energy E; k, Boltzmann's constant; N_C, the effective density-of-states in the CB] is assumed. However, the value of T_0 calculated from Eq. (6) (for instance, $T_0\simeq 700$ K for $\gamma=0.7$) is sometimes unrealistically larger than the CB band-tail slope obtained from time-of-flight studies ($T_0\simeq 300$ K).[11] Furthermore, the model cannot account for the γ values smaller than 0.5 found for n-type films.[12] To reconcile the difficulty of the model, effects of deep states, i.e., dangling-bond (DB) states, or continuous states induced by impurities on γ have been considered.[12,13]

Another important nature of γ to be explained is that it profoundly depends on the dark Fermi level E_F. It has been experimentally shown that γ approaches unity when E_F comes closer to midgap $E_i[=(E_C+E_V)/2]$ either by light boron doping[14] or by the field effect,[15] while it decreases to a value even smaller than 0.5 as E_F moves towards E_C. The E_F dependence of γ suggests a change in the nature of recombination centers located around midgap with the movement of E_F. Vaillant and Jousse presented a different kind of model[16] in which detailed balances for tail states acting as traps and DB states with positive correlation energy acting as recombination centers are considered, and numerically showed that γ changes in accordance with a change in the occupation probability of DB states with the position of E_F. γ becomes unity in the vicinity of $E_F=E_i$ and decreases as E_F departs from E_i as was experimentally shown. It is important to note that $E_F=E_i$ is also realized when the intrinsic a-Si:H layer is depleted in diodes with blocking contracts by applying reverse-bias voltages. In that case, linear photocurrent-light intensity dependences are commonly observed.[17] Thus there is a one-to-one correlation between γ and E_F, and in particular, $\gamma=1$ is equivalent to $E_F=E_i$.

Returning to the main problem of the different $\mu\tau$ values obtained from SS-SPC and CC or JR measurements, it should be noted that the latter measurements are usually performed under the depletion conditions mentioned previously. Under these conditions, the dielectric relaxation time becomes larger than the excess carrier relaxation time. Therefore we can expect that the same $\mu\tau$ values would be obtained for the two classes of measurements if E_F could be moved to E_i for the Ohmic planar configuration either by boron doping or field effect. It has been shown that light B doping moves E_F toward E_i and γ increases up to unity.[14] However, $\mu\tau$ can be changed by the incorporation of charged DB states, not simply by the change of the position of E_F.[7] This prevents strict comparison of the $\mu\tau$ values. A better method is to measure the photocurrents of TFT configuration by changing the gate voltage V_G. In this case, E_F in the a-Si:H layer can be changed independently to other conditions such as the excitation intensity and source-drain bias voltage. Kagawa, Matsumoto, and Kumabe investigated E_F dependence of the photoconductivity of a-Si:H by this method.[15] However, we cannot know the $\mu\tau$ values in the depletion (negative gate bias) region for lack of detailed data (device sizes). Furthermore, it is more important to perform the two classes of measurements using the same films. We therefore performed a TFT photocurrent measurement and estimated the $\mu\tau$ product for the completely depleted case.

The TFT was fabricated on an n^+ crystalline Si substrate. First, a-SiO_2 insulator ($>10^{15}\,\Omega^{-1}\mathrm{cm}^{-1}$) layer was deposited to a thickness of 4000 Å by plasma decomposition of SiH_4 and N_2O. Undoped a-Si:H was deposited to a thickness of 4700 Å on the SiO_2 layer by plasma decomposition of SiH_4 under an optimized condition. Aluminum coplanar electrodes 0.5 mm apart were evaporated with a metal mask, and the surrounding a-Si:H layer, excluding the electrodes and between them, was etched away by a CF_4-O_2 plasma. The photocurrents for uniformly absorbing light ($\lambda=660$ nm, 17 μW cm^{-2}) and its intensity dependence [Eq. (5)] were measured as a function of V_G, and $\mu\tau$ and γ values were calculated using Eqs. (1)–(3) and values $\eta=1$, $\alpha=1\times10^4$ cm^{-1}, $E=10^2$ V/cm, and $R=0.3$.[18]

Figure 1 shows the $\mu\tau$ and γ values as a function of V_G together with the dark current. As the positive bias increases, $\mu\tau$ and the dark current increase while γ decreases. In contrast, as the negative bias decreases, $\mu\tau$ monotonically decreases and γ slightly increases, indicating that inversion or hole accumulation does not occur in this bias range. This is in contrast to the result of Kagawea, Matsumoto, and Kumabe[15] However, the condition $\gamma=1$ was unfortunately not obtained in the present study. We then estimated the $\mu\tau$ product for $\gamma=1$ by plotting the $\mu\tau$ values as a function of γ, as is shown in Fig. 2. Although some scatter exists, we estimate the $\mu\tau$

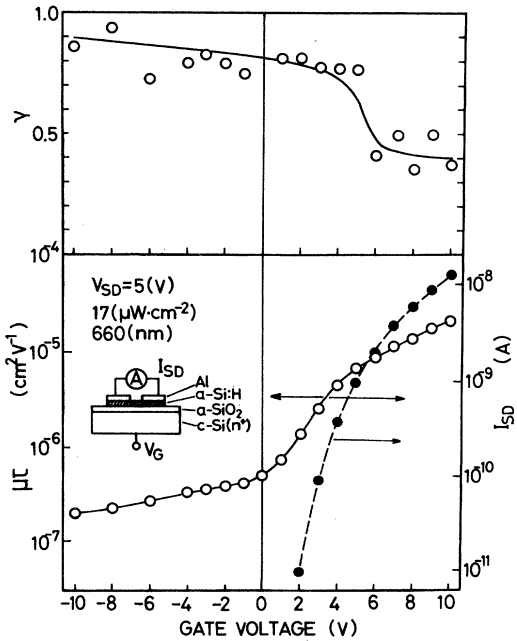

FIG. 1. Gate-voltage dependence of the mobility-lifetime product ($\mu\tau$) (open circles), source-drain current in the dark (I_{SD}) (filled circles), and the exponent (γ) in the excitation intensity dependence of the photocurrent. The inset is the schematic cross-sectional view of TFT.

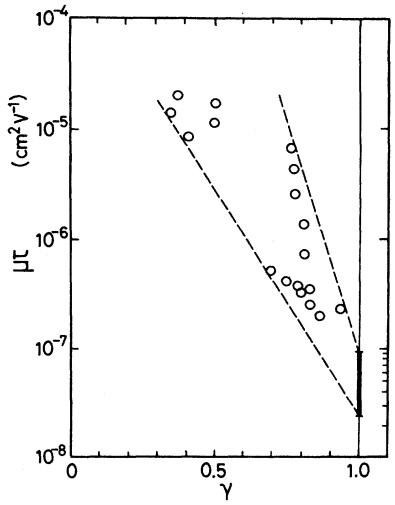

FIG. 2. Mobility-lifetime products ($\mu\tau$) vs exponent (γ).

product for $\gamma=1$ to be $(2\text{-}9)\times10^{-8}$ cm^2/V. This value is very near the $\mu\tau$ value (2×10^{-8} cm^2/V) previously deduced by the bias voltage dependence of the photocurrent (SS-PPC) for the Schottky diode using the *a*-Si:H prepared under the same condition.[7] From this result, we can see that the $\mu\tau$ product obtained from coplanar measurements approximately agrees with that obtained from diode measurements if E_F can be located at E_i and recombination is monomolecular ($\gamma=1$). We (can) conclude that the discrepancy is primarily due to the difference in E_F for the two classes of measurements, that is, higher E_F levels for the SS-SPC measurements and $E_F\simeq E_i$ for reverse-biased diode measurements. It is not essential for a measurement to be steady state or transient. Indeed, the $\mu\tau$ product from our SS-PPC measurement is comparable to typical values (10^{-9}-10^{-7} cm^2/V) obtained from CC or JR measurements.[3-5]

Finally we will briefly consider the meaning of the lifetime τ. Clearly τ in the SS-SPC measurement is the electron-hole recombination time τ_R while that in reverse-bias diode measurements, in which inhomogeneous excitation is usually used, is the deep-trapping time τ_T. For simplicity, following the Shockley-Read recombination model[19] for recombination at a single kind of center, τ_R is related to τ_T as[20]

$$\tau_{Rn}=\tau_{Tn}+\frac{n}{p}\tau_{Tp}\,, \tag{7}$$

where n and p are the densities of free electrons and holes, respectively. The subscripts n, p indicate electrons and holes, respectively. This simple model well describes the features of the recombination of *a*-Si:H if we assume that the primary recombination center is DB states. The shallow states (tail states) only affect the magnitude of mobility. For undoped *a*-Si:H, the relation, $n\gg p$ is satisfied because undoped *a*-Si:H is slightly *n*-type (i.e., $E_F>E_i$), resulting in $\tau_{Rn}>\tau_{Tn}$. This is also consistent with the argument of Schiff.[6] In contrast, when E_F is located at E_i as in reverse-bias diode measurements, $n\simeq p$ is satisfied if $N_C=N_V$ (N_V represents the effective density of states in the valence band) is assumed, and Eq. (7) reduces to $\tau_{Rn}\simeq\tau_{Tn}+\tau_{Tp}$. Since τ_{Tn} and τ_{Tp} are inversely proportional to the capture cross sections σ_n and σ_p, respectively, and it has been shown that σ_n and σ_p are similar in magnitude for *a*-Si:H,[21] τ_{Rn} also is similar to τ_{Tn} or τ_{Tp}. Thus, strictly speaking, τ_{Rn} does not necessarily become equal to τ_{Tn} even when $E_F=E_i$, but $\tau_{Rn}>\tau_{Tn}$. This may explain the fact that the estimated $\mu\tau$ product for $E_F=E_i$ by the TFT measurements is somewhat larger than that from the SS-PPC measurement. We can estimate the $\mu\tau(=\mu_0\tau_f)$ product for $E_F=E_i$ to be 3×10^{-8} cm^2/V, if we assume ballistic capture of free electrons by DB (i.e., $\tau_{Tn}=1/\sigma_n v N_d$) (Ref. 22) where μ_0 is the microscopic mobility ($=10$ cm^2/Vs),[23] τ_f is the free lifetime, v is the thermal velocity ($=10^7$ cm/s), and N_d is the typical DB density (10^{16} cm^{-3}). This estimated value is comparable with our experimental result for the case $E_F=E_i$.

In summary, we studied the E_F dependence of $\mu\tau$ by the gate-bias-voltage dependence of TFT photocurrent to clarify the origin of the different $\mu\tau$ values from coplanar and reverse-bias diode measurements. It was found that $\mu\tau$ from the TFT measurement coincides approximately in the intrinsic limit ($E_F=E_i$ or $\gamma=1$) to that from the reverse-bias photocurrent measurement on the same *a*-Si:H film. From this result, we concluded that the discrepancy in $\mu\tau$ is primarily due to the different positions of E_F for the two classes of measurements.

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