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Persistent photoconductivity in a-Si:H/a-SiN$_x$:H layered structures

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A persistent photoconductivity effect, which lasts for many minutes at room temperature after a brief exposure to light, is observed in multiple thin layers of alternating a-Si:H and a-SiN$_x$:H. In addition, the samples in the dark are found to get polarized upon application of low electric fields, parallel to the layers. The depolarization takes several minutes at 300 K. The results are explained in terms of deep traps at the interfaces.

A new class of materials, with very interesting properties, can be synthesized by depositing alternate layers of thin films of amorphous materials. A number of such multilayer structures has been prepared and investigated at Energy Conversion Devices[1] during the past several years. Recently, there has been a great deal of interest in the study of layered structures of amorphous silicon alloys. These include undoped heterostructures[1-7] consisting of alternate ultrathin layers of two different amorphous semiconductors [e.g., a-Si:H/a-SiN$_x$:H (Refs. 2–7), a-Si:H/a-SiO$_x$ (Ref. 4), a-Si:H/a-Si$_{1-x}$C$_x$:H (Refs. 5–7), a-SiGe:H:F/a-Si:H:F (Ref. 1), a-Ge:H/a-Si:H (Refs. 1,2,5,7), etc.], as well as doped structures in which the adjacent layers of a-Si:H are differently doped[8,9] (e.g., *npnp*, *nipi*, etc.). Most of the structures are reported to have smooth layers to better than 5 Å, and many interesting effects, similar to the quantum size effects in crystalline superlattices[10,11] have been found. An increase in the optical and electrical gaps,[2,4,5] an enhancement of photoconductivity,[3,12] and a shift in the photoluminescence peak[2-4] are some of the effects reported in the multilayered amorphous silicon-based heterostructures. In the *np*-layered structures of a-Si:H, a large persistent photoconductivity (PPC) at 300 K has been found after a brief exposure to light.[8,9,13] This PPC has been tentatively ascribed to the separation of photoexcited carriers by the internal fields.[8,14] Similar PPC effects have been seen earlier in crystalline GaAs/Al$_x$Ga$_{1-x}$As quantum-well structures,[15-18] but at lower temperatures (< 77 K).

We present here our studies on the multilayers of a-Si:H/a-SiN$_x$:H, which include the observation of a so far unreported PPC effect in these heterostructures. We also observe polarization effects in the samples when subjected to low electric fields in dark. The results are explained in terms of deep traps at the interface.

The a-Si:H/a-SiN$_x$:H structures are prepared by the glow discharge method which consists of depositing alternate layers of a-Si:H and a-SiN$_x$:H by admitting silane mixed with hydrogen and with ammonia, respectively, using a computer controlled apparatus. The a-SiN$_x$:H thickness is kept fixed at 20 Å, whereas the a-Si:H layer thickness (d) is varied between 20 and 750 Å. The pressure during discharge is 0.3 torr, the rf power is 300 mW cm^2, and the deposition rate is ≈ 1 Å/s. The plasma is not quenched while switching from one gas to another and the pumping speed is high enough to avoid a contamination of the next layer from the residual gas used for growth of the previous layer. X-ray diffraction shows sharp boundaries (to within 5 Å) between the layers.

The heterogeneous layered structures show many properties similar to the results from other laboratories.[2-7] We find a large anisotropy between the electrical conduction measurement made parallel and perpendicular to the layers,[12] an increase in the optical gap as the a-Si:H layer thickness d decreases below ~ 30 Å, an increase in sub-band-gap absorption as the number of interfaces increases, and transfer doping effects in electrical conduction.

Electrical measurements for our experiments are done in the coplanar geometry. Using a colloidal solution in an organic liquid, graphite electrodes about 1 mm apart are applied to the top of the structure after scratching it with a diamond scribe to make sure that the contact is made to all the layers. The conductivity measurements parallel to the layers are hampered not only because the samples are non-Ohmic even for fields as low as 10 V/cm, as reported in the literature,[12] but also because the current changes as a function of time, after application of the measuring voltage, over a period of several minutes. For a given sample, the manner in which this variation occurs depends on the voltage applied, temperature, and on the previous history, e.g., previous exposure to electric fields and light. Even for low fields (50 V/cm) the transient current can differ by as much as 100% as compared to the steady-state value. But the steady-state current always seems to reach the same value, after waiting for a sufficiently long period of time, which is found to be several hours, in some cases. Upon switching off this low field, a current in the opposite direction (depolarization current, I_d) is found to flow, which at room temperature takes a few minutes to decay. Figure 1 shows the decay of I_d for a sample with 100 pairs of a-Si:H, a-SiN$_x$:H layers, which was polarized for 50 s by applying 50 V ($E_{pol} \approx 500$ V/cm) at 270, 300, and 350 K. As is evident, the decay is not a single exponential and is faster at higher temperatures. The magnitude of the depolarization current decreases as the duration and the magnitude of the polarizing field are decreased. Annealing to ~ 400 K reduces the depolarization currents to below the detection limit ($< 10^{-13}$ A).

These transient effects are not present in unlayered a-Si:H films of equivalent thickness and are more prominent for films with larger numbers of layers.

For the observation of persistent photocurrents (PPC), the following procedure is followed. The sample is heated in vacuum to 150 °C and kept at this temperature for ≈ 15 min in dark. Then, it is cooled to the desired temperature and a bias of 50 V is applied parallel to the layers. After the current reaches a steady value (i_d) in the dark (which takes

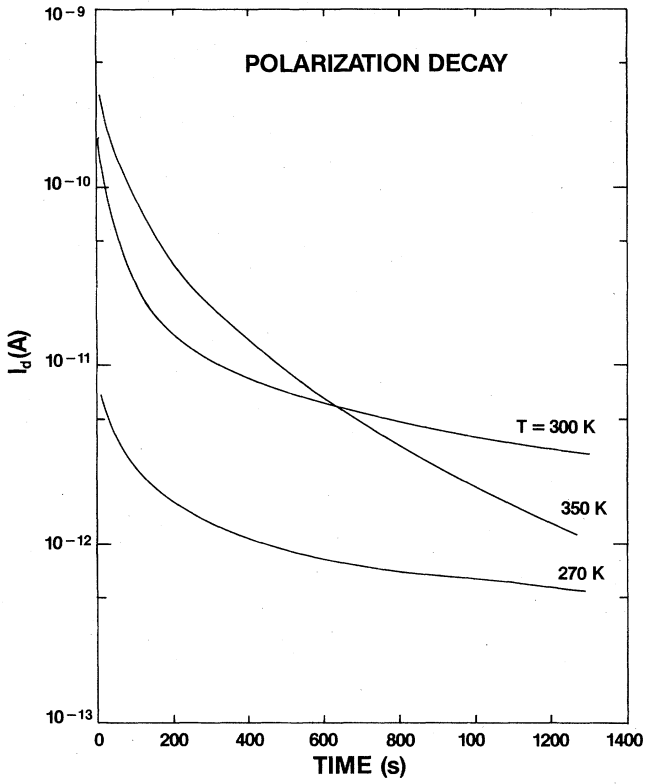

FIG. 1. The decay of polarization at 270, 300, and 350 K for an amorphous heterostructure consisting of 100 pairs of 20-Å-thick alternating layers of *a*-Si:H and *a*-SiN_x:H (sample No. 3), after being polarized by applying 50 V for 50 s parallel to the layers.

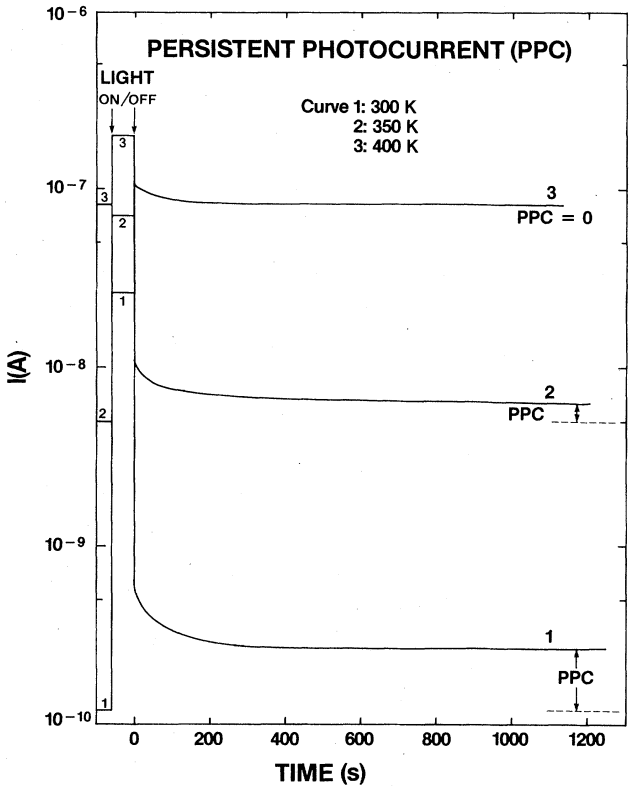

FIG. 2. Persistent photocurrent (PPC) measured at 300, 350, and 400 K for sample No. 3 (*a*-Si:H/*a*-SiN_x:H; 20 Å, 20 Å, 100 cycle), after exposing it to 10-mW/cm^2 filtered light (6000 Å $\leq \lambda \leq$ 8000 Å) for 60 s.

several minutes) the sample is exposed to the filtered light from a tungsten-halogen source (6000 Å $\leq \lambda \leq$ 8000 Å) and the resulting photocurrent (i_{ph}) is measured. The maximum intensity and exposure times used are 10 mW/cm^2 and 60 s, respectively. Upon switching off the light, the current drops by several orders of magnitude quite quickly, but then decays slowly and an excess current (i_{pc}) persists for several minutes, even at room temperature (see Fig. 2). The magnitude of this effect depends upon the exposure time, intensity, and temperature, and is more for longer exposures, higher intensities, and lower temperatures. Further, it becomes more pronounced as the number of layers increases. Table I shows the results for three samples at 300 K, with measuring field $V = 50$ V, having 8, 30, and 100 pairs (cycles) of amorphous silicon and amorphous-silicon-nitride layers. The ratio of the persistent to dark current (i_{pc}/i_d) increases progressively as the number of cycles increases. Further, exposure to sub-band-gap light does not quench the PPC and sometimes results in a slightly higher PPC.

TABLE I. Dark current (i_d), photocurrent (i_{ph}), and persistent current (i_{pc}) measured 30 min after a 60-s exposure to 10-mW/cm^2 filtered light.

Sample number, layer thickness, and cycles	Dark current (i_d) (A)	Photocurrent (i_{ph}) (A)	Persistent current (i_{pc}) (A)	i_{pc}/i_d
No. 1 *a*-Si:H/*a*-SiN_x:H 750 Å, 20 Å, 8 cycles	1.3×10^{-10}	3×10^{-6}	1.8×10^{-10}	1.4
No. 2 200 Å, 20 Å, 30 cycles	2.3×10^{-8}	6×10^{-6}	3.7×10^{-8}	1.6
No. 3 20 Å, 20 Å, 100 cycles	1.2×10^{-10}	3×10^{-8}	2.6×10^{-10}	2.2

The slow polarization and depolarization of the samples upon application of the small electric fields can be explained in terms of an interfacial polarization. This is sometimes also referred to as Maxwell-Wagner-Sillars polarization.[19,20] It results from the formation of charged layers at the interfaces due to inhomogeneities.[19] During this process, free charge may migrate over microscopic distances with subsequent trapping. But in order for this to occur, the current should flow through the inhomogeneities. Since a coplanar geometry is used, the current flows parallel to the layers in the present case. However, it is likely that near the interface there are inhomogeneous regions which extend into the two layers. This extension need not be large, since, because of charge transfer between a-Si:H and a-SiN$_x$:H layers, most of the current is likely to flow in a-Si:H very close to the interface. Hence, it is not unlikely that a large number of the electrons encounter these interfacial inhomogeneities. The long time constants and the observation that the polarization effects are more pronounced for films having a larger number of layers, and are not noticeable for pure a-Si:H or a-SiN$_x$:H films, also support the view that these effects are related to the deep traps at the interfaces. Further, it implies that although the interfaces appear to be structurally quite sharp, the material in the immediate vicinity is probably more heterogeneous than a-Si:H or a-SiN$_x$:H alone.

We find that the total integrated charge released during depolarization for films having different numbers of layers, scales approximately linearly with the number of interfaces. This also indicates that these transient effects may be related to the states at the interface. The number of these states estimated from the integrated charge is about $10^{11}\,\mathrm{cm}^{-2}$. This agrees wih the estimates obtained from the photothermal deflection[4,12] and electroabsorption measurements[21] on these structures in our laboratory and elsewhere.

We now turn our attention to the persistent photoconductivity (PPC) effects. As pointed out earlier, PPC has been observed in GaAs/Al$_x$Ga$_{1-x}$As heterostructures and also in doping-modulated–alternate-layer structures. In selectively doped GaAs/Al$_x$Ga$_{1-x}$As heterojunctions, two mechanisms giving rise to PPC have been identified:[18] (i) electron photoexcitation from the DX centers in Al$_x$Ga$_{1-x}$As layer and (ii) electron-hole generation in bulk GaAs with a charge separation at the interface. Since the PPC effect in a-Si:H or a-SiN$_x$:H alone is negligible, the possibility of a special center in either of the bulk materials giving rise to PPC can be ruled out. Let us now consider the possibility of charge separation. In doped alternate layers, the photoexcited electron-hole pairs can be separated by the p-n junction fields and consequently reside in spatially different regions. In undoped heterostructures like a-Si:H/a-SiN$_x$:H, charge transfer causes band bending at the interfaces. Electrons trapped in the accumulation layer may have to overcome a barrier before recombining with a hole and this may result in PPC. The estimated band bending, however, is less than 0.5 eV and a barrier of this magnitude cannot give rise to the long time constants at room temperature observed in our experiments.

Our observation that PPC is observed only in the layered structure and not in the individual materials and the fact that it increases as the number of of interfaces is increased indicate that deep trapping at the interfaces may be responsible for this effect. As we have pointed out earlier, the a-Si:H/a-SiN$_x$:H interface is characterized by a large number of interface states. Trapping and detrapping from these states may give rise to PPC. We note, however, from Table I that i_{pc}/i_d increases very slowly as the number of interfaces increases. This is unlike the case of the depolarization experiment, where the total charge increases almost linearly with the number of layers. We should mention that the position of the dark Fermi level in the a-Si:H/a-SiN$_x$:H system depends on the thickness of the a-Si:H layers because of charge transfer effects. For very thin layers (< 30 Å), quantum effects and inhomogeneous growth can also affect the conduction process. The dependence of i_{pc} and i_d on layer thickness is therefore rather complicated and this might be responsible for the observed sublinear behavior of i_{pc}/i_d on the number of interfaces.

From Fig. 2, we find that the photoconductivity decreases very fast initially and then decays slowly. Since the decay does not obey a single exponential, detrapping from a distribution of traps, rather than a single level, seems to be responsible for PPC. This makes it difficult to discuss our results quantitatively, since nothing is known about the distribution of traps at the interface. For simplicity, however, if we limit our discussion to the deepest traps, we note that the time constants for these traps exceed 10^4 s. Following Rose,[22] the response time τ_0 in a material with traps located E_t below the conduction-band edge, E_c is given by

$$\tau_0 = \left(1 + \frac{N_t}{N_c} \exp\frac{|E_c - E_t|}{kT}\right)\tau \ ,$$

where N_c is the density of states at E_c, N_t is the trap density, and τ is the recombination lifetime. Assuming $N_c = 10^{19}$ cm^{-3}, $N_t \approx 10^{11}$ cm^{-2}, and values of τ ranging between 10^{-8}–10^{-6} s, we find that a response time of 10^4 s is possible for $E_c - E_t$ lying between 0.8 and 0.7 eV. Similar time constants are also possible for shallower traps, if they have barriers associated with them.

In conclusion, an enhanced dark conductivity (PPC) in a-Si:H/a-SiN$_x$:H heterostructures has been observed after brief exposures to light. Application of small electric fields parallel to the layers results in a polarization of the samples in dark. Both the effects are persistent at 300 K and increase with an increasing number of layers. The results have been interpreted in terms of deep trapping at the interfaces.

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