Physics of Semiconductor Devices

Proceedings of The Third International Workshop

Editors

S C JAIN AND S RADHAKRISHNA

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Physics of Semiconductor Devices

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PREFACE

COSTED, Committee on Science and Technology in Developing Countries was established by the International Council of Scientific Unions in 1966 to consider the most effective methodologies of using Science and Technology to assist developing countries. COSTED has been working in close collaboration with many national members in organising a number of scientific seminars, workshops and conferences in developing countries in order to provide opportunities for a large number of scientists in the developing countries to participate in these activities and interact with the top scientists from different parts of the world. Under this programme COSTED has already organised activities in the subject areas of Tissue Culture, Biotechnology, Thin Solid Films, Lasers and Their Applications, Rural Technology, Semiconductor Devices, Optical Communications, Experimental Techniques for Surface Analysis, Microprocessor interfacing with instruments and such other areas. In all these programmes leading experts in the subject give keynote addresses followed by indepth discussions and laboratory sessions. The first two International Workshops on 'Physics of Semiconductor Devices' were organised in New Delhi in 1981 and 1983. This third International Workshop is being organised at The Indian Institute of Technology in Madras where the Physics department has been actively engaged in Experimental Solid State Physics work for over two decades now. This workshop is being attended by over three hundred distinguished scientists, and is being sponsored by a number of agencies in India. We are grateful to all of them for their support.

25 November 1985

S. C. Jain
S. Radhakrishna

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RECENT FUNDAMENTAL AND APPLIED DEVELOPMENTS IN THE AMORPHOUS SILICON FIELD

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Abstract:

The review begins with a brief discussion of the glow discharge deposition technique for the production of electronically viable amorphous silicon (a-Si) specimens and devices. This is followed by the first main section dealing with the study of transport and lifetimes of excess electrons and holes. Results from fast transient experiments on junction structures are presented and the information they provide on carrier interaction with tail states and deep lying dangling bond states is discussed. The second part of the paper is concerned with recent device developments, grouped under two main headings. First we shall deal with the a-Si field effect transistor and its possible applications and then go on to discuss devices developed from various a-Si junction configurations. The latter include photovoltaic cells, electrophotographic layers and memory junction devices.

1. INTRODUCTION

The development of the amorphous silicon (a-Si) field during the last decade has been an exciting and challenging experience for all of us involved in it. The fundamental work on a-Si prepared by the glow discharge technique had by the mid-1970s established the remarkable electronic properties of the material which could be controlled over a wide range of substitutional doping. Within a few years major industrial laboratories had entered the field and impressive applied developments, in some cases already on an industrial scale, are now taking place.

I should like to begin this review with a brief discussion of an important topic common to all developments - the glow discharge deposition of the a-Si film. On the fundamental side I shall confine myself to some of the recent work which has led to our present understanding of the electronic transport and the defect structure in the material. The final section deals with a number of device developments which are of particular current interest.

2. DEPOSITION OF a-Si FILMS IN A GLOW DISCHARGE PLASMA

At the present time the most promising method for the production of electronically viable a-Si layers is by the decomposition of a gas, such as silane (SiH_4), in a radio-frequency (r.f.) glow discharge plasma, normally excited by a 13.6 MHz generator. Our understanding of the complicated processes taking place in the 'weak' plasma of a typical deposition unit is still rather limited; this applies particularly to the details of the important interactions taking place between the growing film surface and the plasma. It is therefore not surprising that the design of the reactors and the optimum deposition conditions developed largely on an empirical basis.

2.1. Laboratory Deposition Systems

Glow discharge preparation units can be divided into two groups, depending

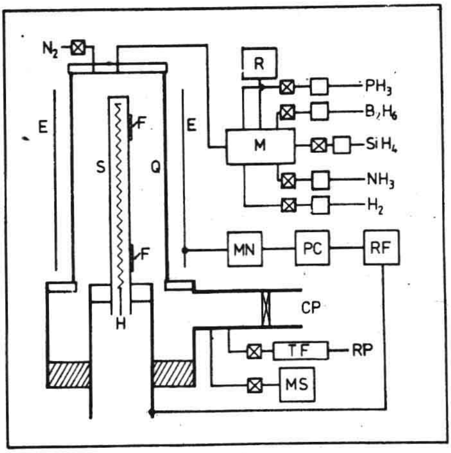

Fig. 1. Vertical, capacitively coupled system, used at Dundee laboratory.

on the method of coupling the radio frequency excitation into the plasma. The first glow discharge deposition of a-Si was carried out in an inductively coupled system by Sterling and his collaborators /1/ and the same approach was adopted in the early work of the Dundee group on the electronic properties of the material /2,3/.

The second type of deposition system employs capacitive coupling. The parallel plate geometry can easily be scaled up for the uniform deposition of larger area specimens. Fig. 1 is a schematic diagram of a vertical system that has been used in the Dundee laboratories during the last few years, particularly for the deposition of multi-layer specimens. The stainless steel specimen holder S and its electrically insulated heater H are mounted vertically to reduce the deposition of small particles. The r.f. field is applied between the external electrodes E which are electrically connected together and adjusted parallel tc the surface of S; both sides of the holder can be used giving a useable area of 300 cm^2. Rotatable 'flaps' F are fitted, which can be operated during a deposition run to shade certain regions of the substrate. The r.f. generator is connected to plates E through a power-controller PC and a matching network MN. The stainless steel gas handling system consists of the five channels indicated, used for substitutional doping, the deposition of silicon nitride and of thin micro-crystalline Si films (strong hydrogen dilution). The channels, each fitted with electronically controlled mass flow-meters, are connected to the mixing chamber M. For cleanliness the whole system can be kept under high vacuum produced by the 3000 ls^{-1} cryo-pump CP.

During operation a rotary pump RP maintains a constant gas flow ($\simeq$ 1 cm^3/min at S.T.P.) through the system at a pressure of 0.1 to 1 torr. It is important to note that the film grows in close contact with the plasma and that its electronic properties are critically dependent on the interactions taking place at the interface. In spite of the simplicity of the basic arrangement, the reproducibility and quality of the specimens can be maintained only by careful attention to all the parameters involved. Electronic properties as well as hydrogen content are also dependent on the dimensions of the system, presumably as a result of floating potentials on surrounding surfaces. It has generally been found that to achieve the lowest densities of gap states, substrate temperatures between 270° and 300°C are required, together with a low level of r.f. power (1 - 10W), just sufficient to maintain a weak glow discharge.

2.2. Large Scale Deposition Units

The reactors used above are useful in the research laboratory for preparing a limited batch of specimens, but they are hardly suitable for industrial production on a larger scale. The rapid growth in the field of a-Si photovoltaic devices has stimulated interest in the industrialisation of the glow discharge technique. In 1981 Kuwano and Ohnishi /4/ of the Sanyo laboratories described the design of what is probably the first industrial plant for the

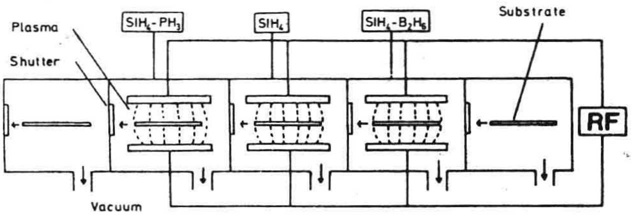

Fig. 2. Industrial glow discharge reactor designed by the Sanyo laboratories /4/

production of a-Si devices. As shown schematically in fig. 2 the system consists of five separate vacuum chambers, connected by vacuum locks. Trays loaded with substrates are placed into the first chamber on the right and then pass in a continuous process through the three central chambers in which boron doped, undoped and phosphorus doped layers are deposited to form the p-i-n photovoltaic junction. The main advantage of separating these stages is that problems arising from dopant contamination are completely avoided. A deposition unit recently developed by Sharp-ECD is designed along similar lines.

It is evident that in industrial production of a-Si devices the deposition rate should be as high as possible, consistent with the electronic properties required for the particular application. In the laboratory units high quality a-Si films are normally prepared at deposition rates of less than $3Å s^{-1}$ and the minimum r.f. power. Under these conditions ion and electron energies in the plasma remain sufficiently low to reduce defect formation at the growing surface to an acceptable level. Possible methods of overcoming this limitation have been investigated with some success. They include modifications in system design /5/ and the use of higher silanes in the deposition /6/.

3. THE DEVELOPMENT OF THE a-Si FIELD

The unique and highly controllable properties of glow discharge Si make it at the present time the most suitable thin film material for basic studies and for a growing range of applications. An interesting feature of the development has been the close relation and short time scale between the fundamental insight into material properties and the exploration of the applied possibilities. As shown by the following summary, most present applications have their origin in one of two fundamental developments:

(i) Study of the density of state distribution by the field effect (1971)	a-Si field effect transistor development, Addressable arrays for Liquid crystal displays and Image sensing, Logic circuits.
(ii) Doping in the a-phase (1975)	p-n, p-i-n junctions. Photovoltaic cells, Photoconductive cells, High-current diodes, Electrophotography, Vidicon Image tubes, Memory junction devices.

The first is the study of the density of state distribution in the mobility gap of a-Si by the field effect technique. These experiments, which we started in 1971 /7, 8, 9/, led to the realisation that a-Si possessed a remarkably low level of gap states - probably the most important single factor in the applied developments. The a-Si field effect transistor (FET) development began in our laboratory around 1976, /10/, based on the experience gained with the field effect experiments.

The second crucial development was the discovery in 1975 /11, 12/ that the electronic properties of the glow-discharge material could be controlled very effectively by substitutional doping from the gas phase; again, this is closely related to the low gap state density of the material. The possibility of doping has opened up the rapidly growing field of a-junction devices which, together with the FET development, will be reviewed in section 5 of this paper.

4. STUDY OF TRANSPORT AND CARRIER LIFETIMES BY TRANSIENT METHODS

Transient experiments, particularly drift mobility measurements, have made valuable contributions to the understanding of electronic transport in amorphous, thin film materials. The first drift mobility experiments on a-Si were published during the early 1970s /2,3/ by the Dundee group and established the general features of electron transport in this material. It is therefore encouraging to find that during the last few years this approach has been applied again in experiments on greatly improved material and interesting papers have been published by several groups. We shall now look at two important aspects of this work and discuss the interpretation of the results. /13,14/.

4.1. Drift mobility and Interaction with Band tail States

These experiments lead to values for the drift mobilities μ_e and μ_h of excess electrons and holes photo-injected into the thin film junction specimens. On the basis of the multi-trapping model they also provide useful information on the interaction of the excess carriers with the tail states during transit and make it possible to deduce the corresponding extended state mobilities μ_c and μ_v. /13,15/

In our laboratory, transient measurements are generally carried out on p-i-n junctions which, in reverse bias, have the advantage of providing a strictly primary transient photocurrent, unobscured by injection from the electrodes. Fig. 3 illustrates the method. The excitation flash from the dye laser ($\lambda \simeq 5300$Å)

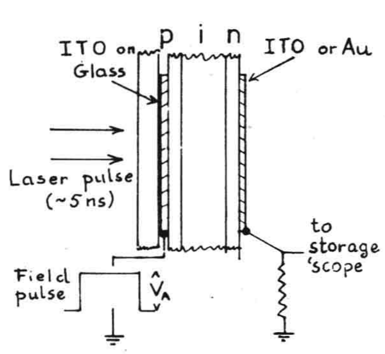

Fig. 3: Specimen and experimental method.

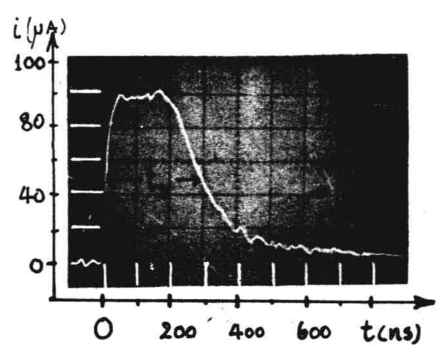

Fig. 4: Observed current pulse./13/.

passes through the 200Å thick, highly doped p- or n-layer and is absorbed in the central region ($1\mu m - 11\mu m$) within about 800Å from the surface. A synchronised 30 μs voltage pulse of height V_A is applied to one of the electrodes about 20 μs before the excitation. A fast storage oscilloscope records the transient signals. Fig. 4 shows a typical transient pulse for excess electrons drifting across an 11 μm thick specimen at room temperature. Evidently, a quasi-thermal equilibrium is rapidly established between extended states and electron tail states extending to about 0.14eV below ϵ_c (see fig. 5). After this i(t) remains constant, so that there is no evidence for any progressive thermalisation as has been suggested /16/. The extraction tail arises from diffusive broadening of the injected pulse during multi-trapping transport.

The transit time t_t is measured as a function of V_A and from the gradient of the linear $1/t_t$ vs V_A plot, the drift mobility μ_e is deduced.

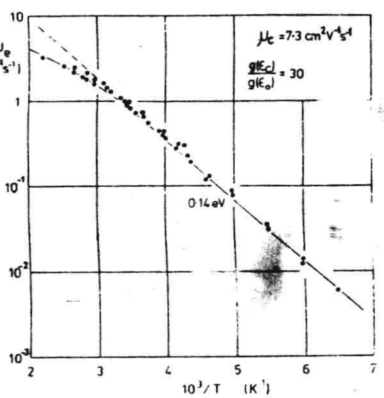

Fig. 5: Temperature dependence of the electron mobility μ_e in a-Si. The solid curve represents the fit to the multi-trapping model with the parameters shown. /15/

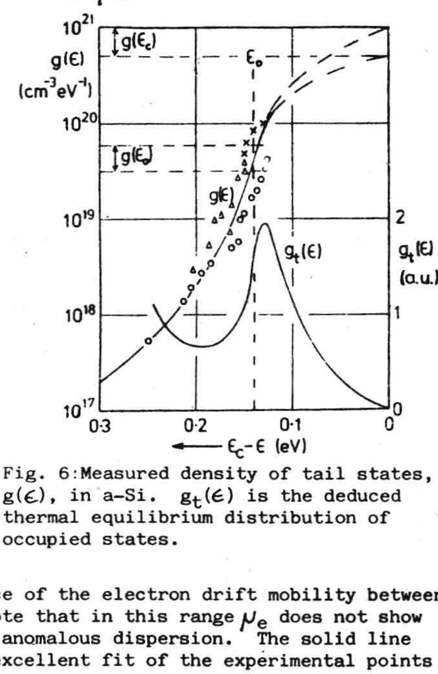

Fig. 6: Measured density of tail states, $g(\epsilon)$, in a-Si. $g_t(\epsilon)$ is the deduced thermal equilibrium distribution of occupied states.

Fig. 5 shows the temperature dependence of the electron drift mobility between 150K and 450K /15/. It is important to note that in this range μ_e does not show any effects that could be associated with anomalous dispersion. The solid line calculated from eqn. (1) illustrates the excellent fit of the experimental points to the multi-trapping model. The latter describes the interactions between the drifting electrons at μ_c and the band tail states, assumed to be in quasi-thermal equilibrium with the extended states during the transit. μ_e and μ_c are then related by :

$$\mu_e \simeq \mu_c \left[1 + \frac{g(\epsilon_o)}{g(\epsilon_c)} \exp\left(\frac{\epsilon_c - \epsilon_o}{kT}\right)\right]^{-1} \qquad (1)$$

In eqn. (1) we envisage that the interaction occurs predominantly with a fairly well-defined range of states around an energy ϵ_o near the bottom of the tail states. This interpretation is strongly supported by the experimental results which show a strictly activated behaviour between 150 and 320K, leading to $\epsilon_c - \epsilon_o \simeq 0.14$eV. At higher T, unity in the denominator of eqn. (1) is no longer negligible, which accounts for the levelling-out of curve. The high temperature region has been investigated by Hourd and Spear /15/, the analysis giving $\mu_c = (10\pm5)\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$. and a density of state ratio $g(\epsilon_c)/g(\epsilon_o) = 30$. It is concluded that values of $\mu_c \gtrsim 500\ \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$, suggested by Silver et al /17/, are entirely incompatible with the interpretation of the experimental results on the basis of a multi-trapping model (in this connection see also ref. 13).

Independent support for the application of eqn. (1) comes from the field effect measurements in fig. 6 /18/ which extend into the electron tail state region; the broken lines represent extrapolations to $g(\epsilon_c)$ values of $5 \times 10^{20}\mathrm{cm}^{-3}\mathrm{eV}^{-1}$ and $10^{21}\mathrm{cm}^{-3}\mathrm{eV}^{-1}$ and the measured value of ϵ_o is indicated. The $g_t(\epsilon)$ curve represents the calculated thermal equilibrium distribution of electrons in tail states and its peak near ϵ_o suggests that these are the states which predominantly control μ_e. The results presented in this section throw considerable doubt on the interpretation of electron transport in terms of an exponential tail state distribution through which progressive thermalisation occurs /16/.

4.2. Interaction with Gap states. Carrier Life times.

Transient methods have been used with some success to investigate the trapping life times τ_e and τ_h of the excess carriers in a-Si, because it is possible in this material to clearly separate the multi-trapping interactions during transport from those involving deep gap states which localise carriers for times much longer than t_t.

We have discussed the problems of transient lifetime measurements in several papers /19,20,21/. Reliable techniques, leading to true 'material controlled' lifetimes in a-Si junctions are the delayed field (D.F.) and interrupted field (I.F.) methods /20/. In both these techniques the internal field in the central region of the junction is reduced to zero during a delay period Δ, either following photogeneration near the top surface (D.F.), or during the subsequent transit of one type of carrier (I.F.). After the field-free period, in which carriers interact with deep centres, all remaining free carriers at ϵ_c and in tail states are swept out by a strong applied field pulse in a time short compared to τ.

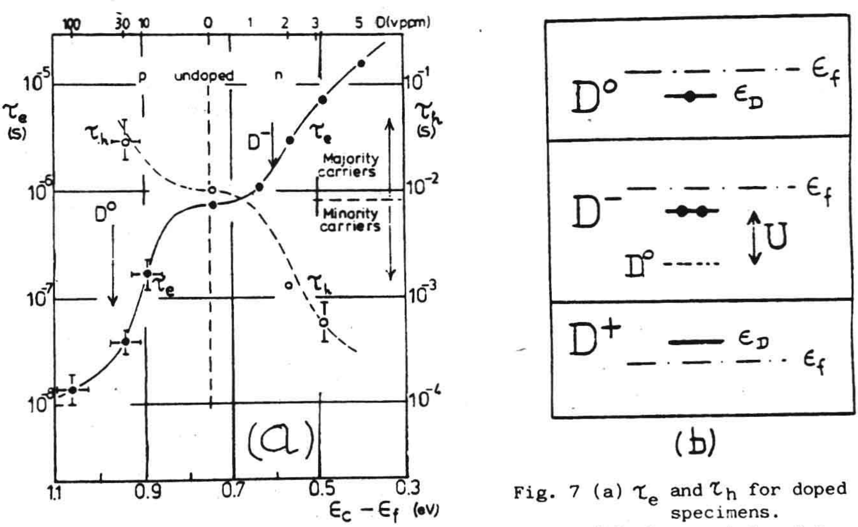

Fig. 7 (a) τ_e and τ_h for doped specimens.
(b) charge state of D-centre.