THE ANALYTICAL STUDY OF THE POROUS SILICON ELECTRICAL CONDUCTIVITY

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Abstract
In this approach we review the electrical conductivity of porous silicon (PS) within this frame work, we study the variation of (PS) conductivity as a function to the limiting parameters such as porosity and temperature. We interpret such conductivity and mobility depended on the properties of the PS layer and the quantum confinements effect in (PS).

<u>**Keywords**</u>**: Porous silicon, Electrical conductivity, Transport mechanisms.**

Introduction

The first observation of porous silicon was reported as early as 1956 by Uhlir, who described the porous layer as a "matty black, brown or red deposit" [1]. In 1990 a report of strong visible photoluminescence by Canham [2] from porous silicon at room temperature [2], formed by electrochemical etching of crystalline silicon, triggered a world-wide research effort mainly aimed at investigating the possibilities for integrating optical functions into all-silicon devices.

Since the paper by Canham [2], in which photoluminescence was linked to quantum confinement, porous silicon has caught the imagination of the materials science community and much work has been done on its fundamental and technological properties [3,2]. The first solid-state electroluminescent devices based on porous silicon consisted of a porous layer on a crystalline substrate [4].

The great interest in the (PS) material is because this material possesses unusual physical properties, the studies of electrical and photoelectrical properties based devices have taken a large space of scientific publication [5,6]. Ben-Chorin [6] has reported that the progress towards Silicon optoelectronics and photovoltaic devices using (PS) layer requires good understanding of the electrical behavior of (PS) layer. Finally we present a theoretical study of (PS) conductivity reaching to understanding the mechanisms of charge carriers inside the (PS) layer.

Theoretical background:

Though extensive offer has gone into investigating the information and optical behavior of porous silicon, several other properties have been by and large ignored. Although luminesescence seems to be the most attractive aspect of this material, it should not be forgotten that a comprehensive physical theory must be able to explain various properties of the system, such as electrical transport, thermodynamic behavior, refractive index, dielectric constant etc. however, the complexities introduced by the apparent inhomogeneity and disordered nature of porous silicon have defied attempts at a precise formulation. As seen in the previous sections, the existing models are mainly phenomenological in nature, based on fit to experimental data, and the analytic approaches are rudimentary. In this section, we provide a brief overview of the various theories and models proposed to explain aspects of porous silicon behavior that have not been discussed so far.

A simple approach to explain the electrical conductivity of porous [7] employs a volume averaging method, which has been used previously to model transport in porous media [8]. The method consists of modeling a multicomponent system according to a set of equations representing the transport of a parameter q together with their initial boundary conditions,

$$D^i \theta^i = 0 \dots\dots\dots\dots\dots\dots (1)$$

Where D is a space time differential operator and i represents the component index. The volume averaging method attempts to average (1) to obtain the effective macroscopic equation.

$$(D^i\theta^i)^i = \frac{1}{V^i}\int_{V^i}(D^i\theta^i)dV = 0 \dots\dots\dots (2)$$

The model employs a three component system consisting of parallel cylindrical rods of crystalline silicon coated with a thin layer of amorphous silicon. The rods are separated by air, which is considered to be a perfect insulator. The electronic transport equations are

$$\frac{\partial\rho_c}{\partial t} = \sigma_c\nabla^2\rho_c$$

$$\frac{\partial\rho_a}{\partial t} = \nabla_s\cdot(\sigma_a\nabla_s\rho_a) - n^{ev}.\sigma_c\nabla\rho_c$$

Where ρ_c, ρ_a are the carrier densities in crystalline and amorphous silicon respectively, σ_c, σ_a the respective conductivities and n^{ev} is the effective charge carriers after etching the normal to the surface at any point and ∇_s is the gradient operator defined on the surface. Averaging (3), (4) according to (2) and simplifying yields the effective conductivity along the direction parallel to the rod axes as,

$$\sigma_{eff} = (1-p)\sigma_c + \frac{A_V\rho_a\sigma_a}{\rho_c(1-p)} \dots\dots\dots (5)$$

Where A_V is the surface area per unit volume and p the porosity. The first tem (volume contribution) is a monotonically decreasing function of porosity. For a good conducting surface (i.e. σ_a large), σ_{eff} exhibits a maximum at a particular porosity. At this optimum porosity, the effective conductivity value can be much higher than that for crystalline silicon. However, there are no experimental results to this effect.

An experimental study of the temperature dependence of the conductance G [9] yielded a Berthelot type of dependence

$$\log G = aT + b \dots\dots\dots (6)$$

Where a and b are constants. This behavior is understood in terms of a network of vibrating sites [10,11], where the tunneling between sites depend only on the distance between them. Thermal vibrations change the distance between sites and consequently the transition probability from one site to another. This results in a temperature dependence of the from

$$\log G = \frac{2\alpha^2 K_B}{k\ln 10}T + b \dots\dots\dots (7)$$

Which is in good agreement with (6) α is the localization constant of the site and k the force constant of oscillation which can be expressed as

$$k = \overline{M}\omega^2 \dots\dots\dots (8)$$

Where ω is the frequency of the infra red active vibrations and $\overline{M}$ the inertia of the linearly oscillating system. This is found to be of the order of the atomic mass.

Such a transport mechanism should be confined to the crystalline surface. The constant b in eq. (6) is determined by the density of states and the transport path geometry of the surface. This could provide a valuable characterizing tool for the porous silicon surface.

In another study [7,8], the conductance of porous silicon at high posities regime (60-88%) was found to vary with voltage V and temperature as [7].

$$G(V,T) = G_0\exp\left[\frac{-E_a}{K_B T}\right]\exp\left[\frac{V}{V^*}\right]^{1/2} \dots\dots (9)$$

Where $E_a(\sim 0.5eV)$ is an activation energy. This suggests a Poole-Frenkel mechanism, further borne out by an experimental verification of the required dependences for V^*

$$\sqrt{V^*} = \frac{K_B T}{e}\left[\frac{e}{\pi\varepsilon_0\varepsilon_r h}\right]^{-1/2} \dots\dots\dots (10)$$

Where e_r is a relative dielectric constant of PS and h is the layer thickness of PS . This varies for samples prepared under different conditions.

There is no proper definition of e_r for a microscopic trap level in inhomogenous systems such as porous silicon. In addition, the high degree of disorder prevents the carriers from moving freely as in a simple Poole-Frenkel model. Further, the effect of quantum confinement on the activation energy E_a has not been discussed. Simplified calculations exist for the applied voltage required for carriers to escape from silicon dots embedded in an amorphous matrix [10].

Diffusion of carriers can occur also by Brownian motion under the influence of Coulomb centers [10]. When the carrier moves a critical distance R_c away from the Coulomb center, the thermal energy becomes equal to the Coulombic energy.

$$K_B T = \frac{e^2}{\varepsilon_0 \varepsilon_r R_c} \quad\text{...............................(11)}$$

In this case, the carrier can overcome the attraction and escape. At room temperature, $R \sim 1000 \ A^0$, so the interpretation of e_r as an effective dielectric constant is reasonable.

Results and Discussion

According to the solution of eq (5), Fig.(1) shows the dependence of the conductivity δ_e ff of (PS) layer on the porosity of the layer at room temperature, From Fig.(1) the effective conductivity δ_{eff} of (PS) samples formed by electrochemical etching process of Si wafer with doping concentration about $10^{15} \ cm^{-3}$ is a function to the porosity of the porous layer(when the temperature is constant). The increasing of the porosities will lead to decrease the conductivity and increases of the resistivity of PS layer. The resistivity of (PS) at high porosities reach to the limit of intrinsic resistivity of bulk crystalline silicon (which is about $2.3 \times 105 \ \Omega.cm$) and some time higher then this value, this is due to several reason as follows:

1-The existence of depleted layer, of charge carriers surrounding the pores [11,12,13].

2-The existence of quantum size effect [12,14].

At porosities with the range 70-80% the resistivity is in the rang $(0.2 - 0.35 \times 10^6)$, and this range is the range of (intrinsic semiconductor) in other word the (PS) layer behaves like a pure semiconductor.

From Fig.(2), shows that the drift mobility of electron (PS) at a constant temperature of PS layer. With different porosities. Also at high porosities 70-80% the mobility of carries has very low values in the range $(300 \times 10^{-4} \_ 460 \times 10^{-4} cm^2/V.sec)$. These low values are due to the increase in the carrier transition time inside the porous material [11].

Especially when the sizes of the silicon is in the nonosizes region.

Fig.(3) represents the variation in the effective conductivity δ_{eff} at different temperature, in the range $(300\text{-}400K^\circ)$ and the dependence of the conductivity on the temperature for porous silicon of low porosities (30-60%) is given by

$$\delta_{eff=} \ \delta_c \ \exp - \frac{E_a}{KT} \quad\text{................................(12)}$$

Where δ_c is the conductivity of the Crystalline Silicon.

E_a is the activation energy, which is about 0.5 ev.

T is absolute temperature K°

This behavior is similar to the case of bulk silicon.

The increasing of temperature will lead to an increase in the conductivity especially at high temperature region. Where at high temperature region the thermal energy is enough to ensure thermal excitation in the silicon nonocrystallites within the (PS) layer. When silicon in a nonosizes region the band gap of (PS) will increase from 1.1 at crystalline silicon to 2.2ev at high porosity region [13].

According to the solution of eq (9) and eq (10), Figs. (4) explain the dependence of the (PS) conductivity on the applied voltage, at temperature from $400k^\circ$ to $300k^\circ$ as show from figure (4) where the equation of the passing current through the (PS) diodes depends on the series resistance (R) on the (PS) layer as show in following equation:

$$I = I_0 \ \exp \frac{V - I \times R}{nKT} \quad\text{...........................(13)}$$

This series resistance is a voltage dependence increased at low voltages the conductivity does not increased by a large a mount i.e. the resistivity is high while at the high voltage the conductivity increase steady due to the reduction of the series resistance. Also this series increased with porosity of the (PS) layer and with decreasing the dielectric constant of the (PS) layer [6,10]. When the dielectric constant decreased i.e. at the high porosities regime the silicon nonocrystallites sizes in (PS) layer decrease to the limit of the quantum confinement. The increasing of the

(PS) layer thickness will increase the resistance of (PS) layer and hence the series resistance (this will true when the dielectric constant does not change (doesn't increase)). But when the dielectric constant decreased especially at high porosities regime. While Fig.(5) represents the dependence of conductivity on temperature at different porosities .The increasing of the (PS) thickness will not means absolutely an increasing of the resistivity of (PS) layer. This will be shown in Fig.(6).
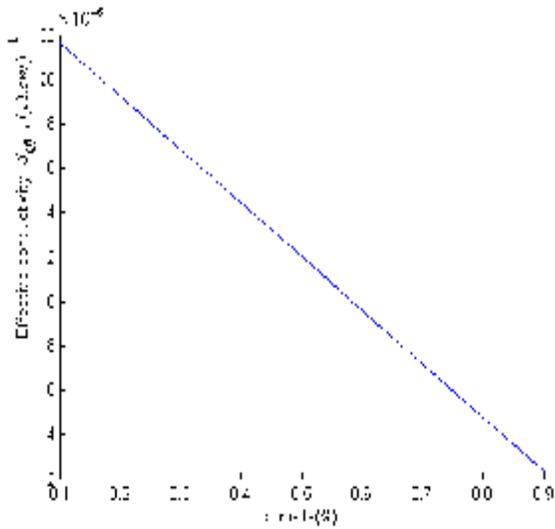

Fig.(1) : Effective conductivity of PS as function porosity at T=300K˚.
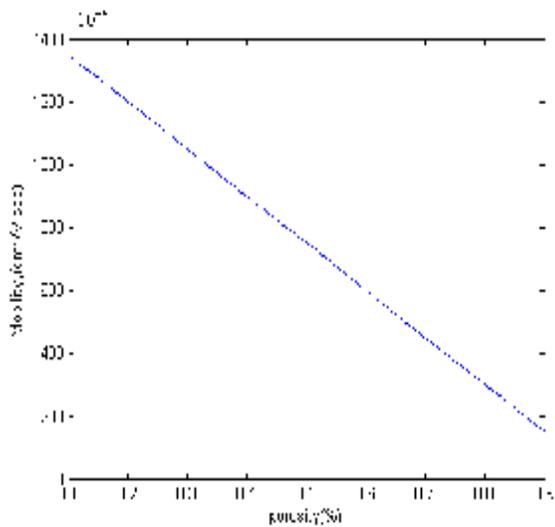
Fig.(2) : Effective conductivity of PS as function porosity at T=300K˚.
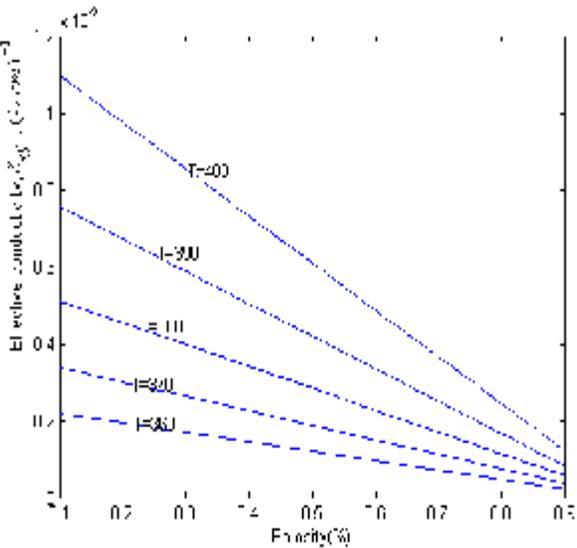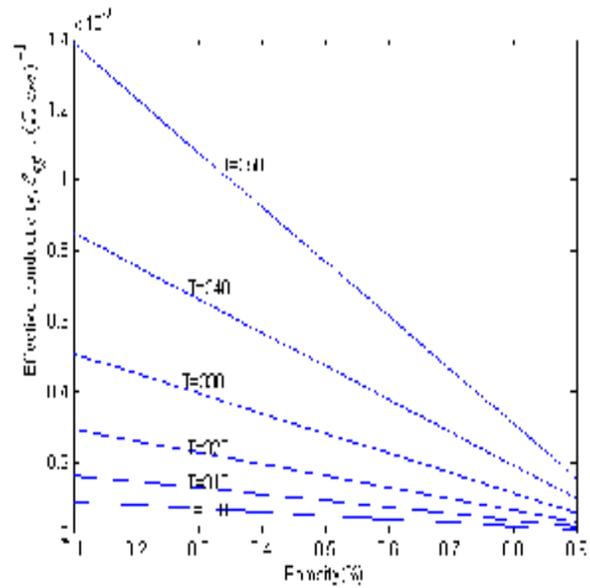
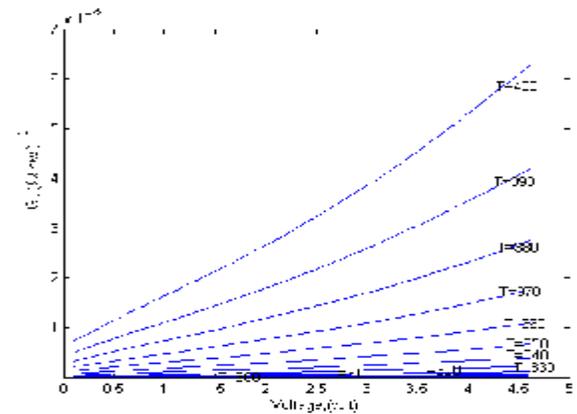*Fig.(3) :Effective conductivity of low porosities (PS) as a function for temperature.*

Fig. (4)Dependence of effective conductivity of high porosity (PS) namely 80% (G) on applied voltage(V) at different temperature.
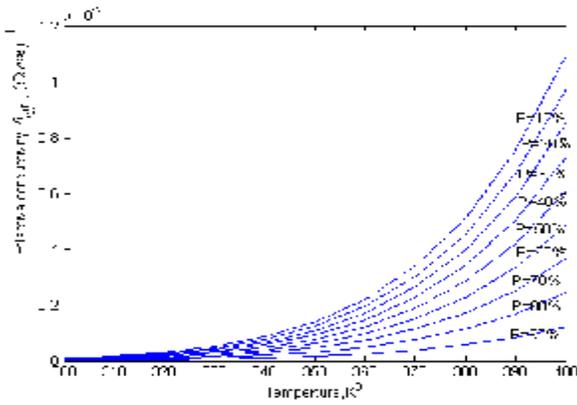
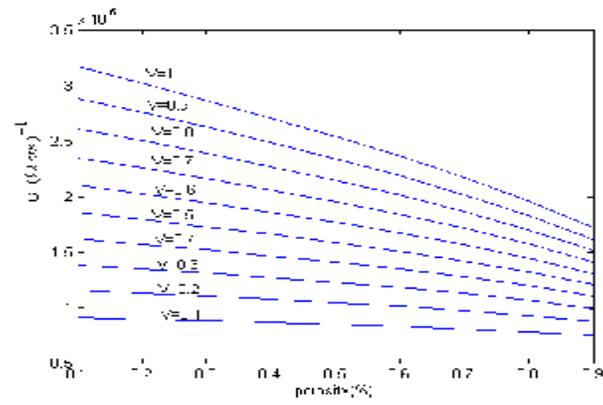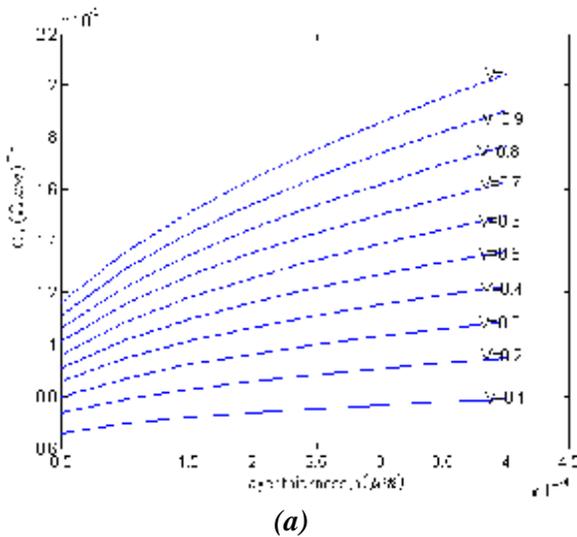***Fig. (5): Eeffective conductivity(G) as a function for temperature at different porosity.***
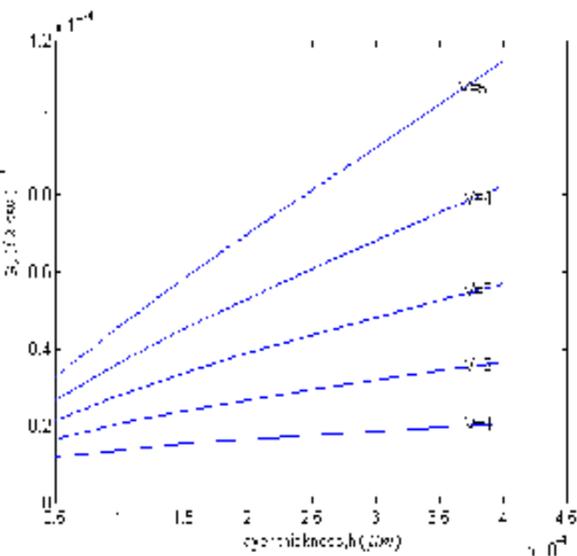

Fig.(7) : The dependence of (G) on porosity at different voltage.

(a)

(b)

Fig.(6) : The dependence of (G) on layer thickness (h) of PS.

Conclusions

In the present context we have learned that conductivity is depended on the porosity of (PS) layer.And its afunction to the morphology namely the nanosizes and pore distributions.

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الخلاصة

في هذا البحث تـم دراسـة خصــائص التوصــيل الكهربائي في السليكون المسامي كدالة للمتغير في المسامية كعامل محدد. النتائج المستحصلة للتوصيلية و التحريكية تم تحليلها بالاعتماد على خصائص طبقة PS و على ظــاهرة الحصر الكمي في السليكون المسامي.