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Laser-Induced Low-Resistance Ohmic Contacts on n-Si

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Abstract: In the present work, the feasibility of formation near-ideal ohmic behavior of In/n-Si contact efficiently by 300 μs duration Nd:YAG pulsed laser processing has been recognized. Several laser pulses energy densities have been used, and the optimal energy density that gives best results is obtained. Topography of the irradiated region was extensively discussed and supported with micrographic illustrations to determine the surface condition that can play the important role in the ohmic contact quality. I-V characteristics in the forward and reverse bias and barrier height measurements have been studied for different irradiated samples to determine the laser energy density that gives best ohmic behavior. Comparing the current results with published results, it is found that these results are competitive and meet the standards of good ohmic contact, specific contact resistance of 1.9×10^{-4} Ω.cm^2 has been obtained at 21.1 J.cm^{-2} laser energy density, which is the lowest value ever reported for In/n-Si.

Introduction

Ohmic contact with low specific resistance is a major standing problem that should be taken in consideration in the design and fabrication of electronic devices, such as bipolar transistors, light emitted diodes, solar cells [1-3] etc... .

Interface states between metal and semiconductor arise from dangling bonds at the interface. When a metal is deposited on semiconductor, interface states pin the interface Fermi level, making the Schottky barrier height independent of the metal work function. Ohmic contacts have been conventionally prepared by decreasing the width of the Schottky barrier so that, electrons can tunnel through it.

Many approaches have been reported to obtain good ohmic contact such as: (1) high-electron concentration under the ohmic contact that can be achieved by conventional doping techniques (diffusion or ion implantation) [4], (2) employing multilayer metallization in which one of the metals deposited is an acceptor impurity and the other metals are donors [5], (3) electrolytical metal tracer technique (known as ELYMAT) [6], and (4) passivation of semiconductor surface to obtain interface states that have a negative Schottky barrier [7].

Laser had been used widely in making ohmic contacts onto semiconducting materials especially Si (n, p). In this study, long pulse Nd:YAG laser was used to produce ohmic contact on Si without using dopant diffusion. Characteristics of ohmic contact were investigated and analyzed.

Experimental Details

n-type monocrystalline Si wafer of (111) orientation and 3-5 Ω.cm resistivity was irradiated by pulsed Nd:YAG laser (1.064 μm wavelength and 300 μs duration) after degreasing and oxide removing of the treated region using HF acid. The irradiation was achieved under different laser energy densities (see Table 1). Topography of the treated region was studied by optical microscope. Indium of 5N purity was deposited onto treated region using thermal resistive technique under pressure down 10^{-6} Torr. The evaporation achieved through special mask, and ohmic behavior of this contact was extensively evaluated.

Table (1). Irradiation parameters.

Effective Spot Area (cm^2)	Energy density ($J.cm^{-2}$)
0.0380	5.9
0.0167	11.3
0.0044	16.8
0.0038	18.4
0.0032	21.1

Results and Discussion

The topography of Nd:YAG treated region is illustrated in the photographs of Figure (1-a, b, c). Figure (1-a) shows a formation of crack with definite angles (60, 120) for laser energy densities (E_d) up to 11.34 J/cm^2, these cracks are certainly formed due to thermal shocks. At 16.8 J/cm^2 of laser energy density, dislocations are produced as shown in Figure (1-b) that mainly due to high cooling rate (quenching) of the hot surface, while protuberances, ripples, and concentric waves are occurred at laser energy densities greater than 16.8 J/cm^2 as was introduced in Figure (1-c) that are probably elucidated by the interaction between incident and scattered radiation by the aerosols in the atmosphere. The malformation of the laser treated surface is expected to act as interfacial traps region after metal deposition which in turns may enhance the ohmic behavior.

Figure (2) demonstrates I-V characteristics in the forward and reverse bias voltages at room temperature of the In/Si contact of unirradiated surface. This figure shows poor ohmic contact behavior indicates that the resistance is non-linear.

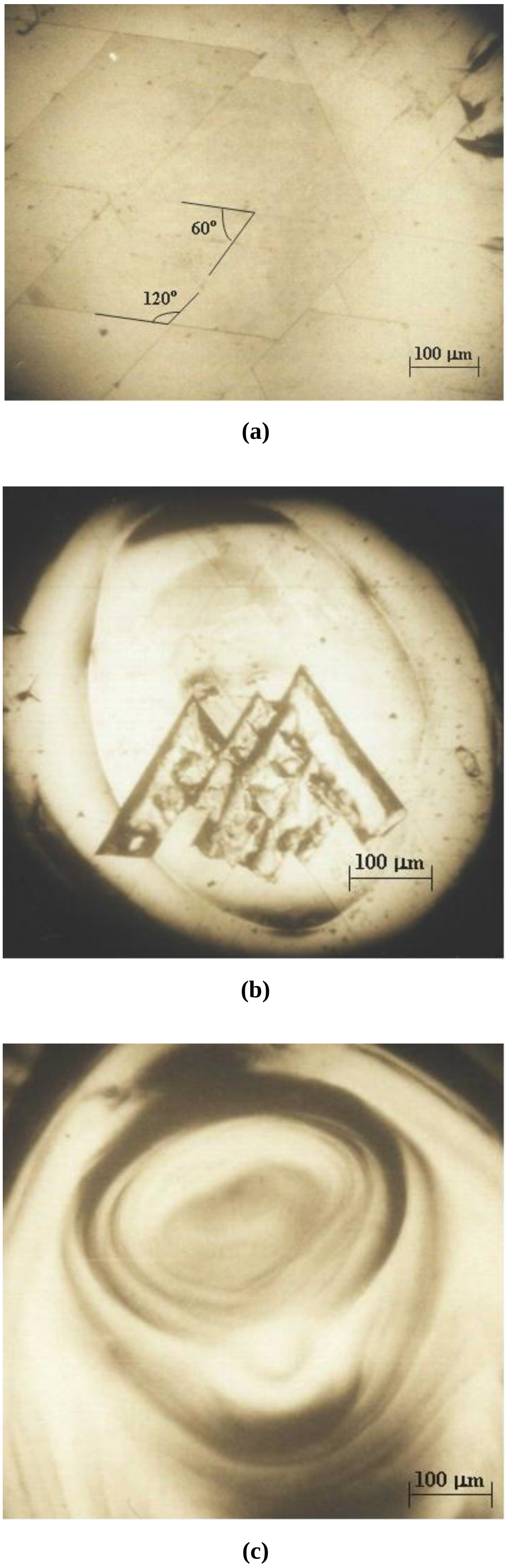

Fig. (1). Photographs of irradiated Si; (a) 11.34 J/cm^2, (b) 16.8 J/cm^2, and (c) 18.4 J/cm^2.

Figure (2) also exhibits that the forward current varies exponentially while the reverse current demonstrates soft breakdown and can be described by two distinct regions. The first region can be explained by a relation similar to that of equation: $\mathbf{I}\ \boldsymbol{\alpha}\ \mathbf{V}$, while the second is depicted by the equation: $\mathbf{I}\ \boldsymbol{\alpha}\ \mathbf{V}^{\mathbf{m}}$ where m<1, where m is an exponent.

Figures (3-a, b, c, d and e) is the measured I-V characteristics in the forward and reverse bias for In/Si contact of Si-treated surface with different energy densities. The first three graphs of the figure (a, b, and c) illustrate clear ohmic behavior (i.e., the resistance is constant and voltage-independent).

The figure also confirms that better ohmic behavior is obtained at energy densities greater than 16.8 J.cm^{-2}, this can be explained as follows: at high energy densities the surface state density becomes more abundant due to increasing the defects.

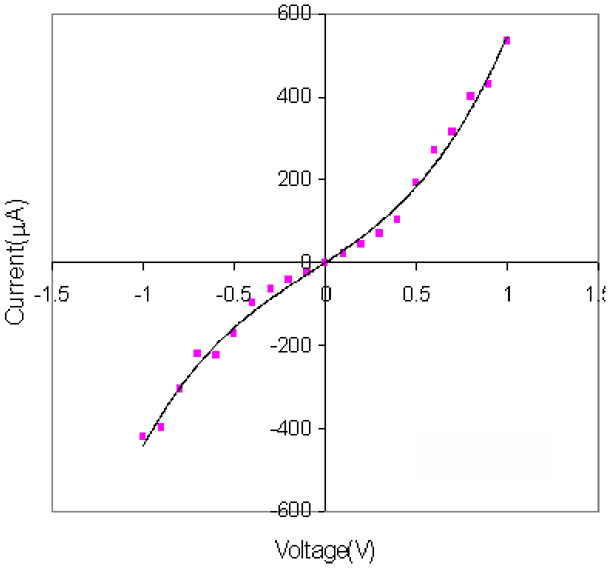

Fig. (2). I-V characteristics of In/Si contact before Si-irradiation.

These surface states will act as interfacial states after electrode deposition which in turns, reduces the barrier height by adding tunneling mechanism to the junction. In addition, laser heating may reduce the segregated impurities and makes the treated region as a heavily doped region. The best results of ohmic behavior are registered at 18.4 J.cm^{-2}.

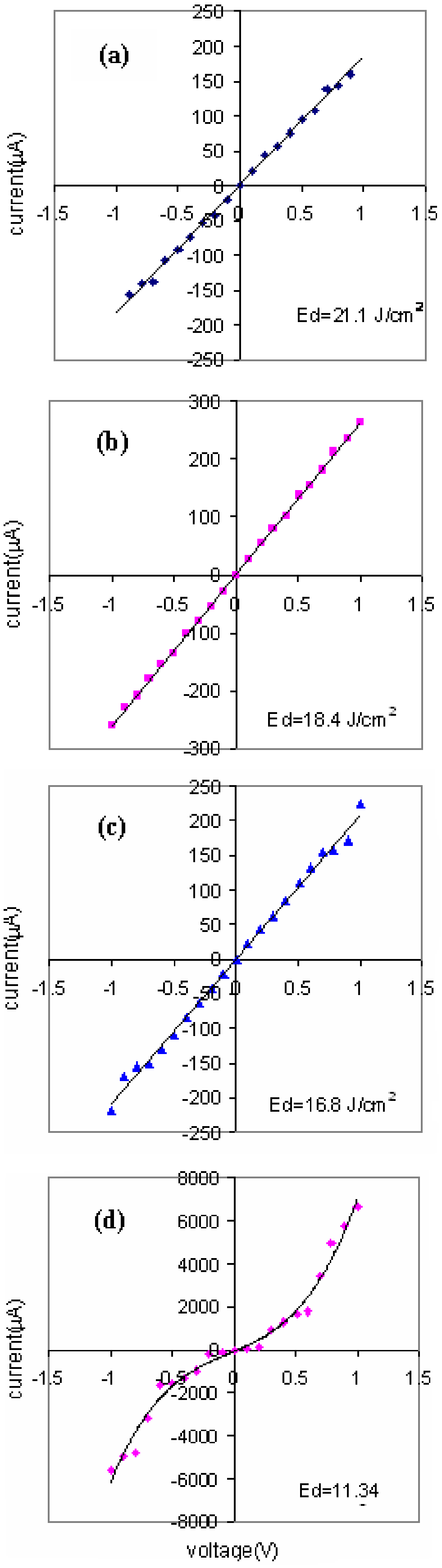

Fig. (3). I-V characteristics of In/n-Si contact irradiated with different energy densities at RT.

The rectification factor (I_f/I_r) at a certain voltage (0.5, 1 V) is 1.02. This result is in full agreement with the results of other work which used Sn as contact on silicon[8]. At 21.1 J.cm^{-2}, ohmic behavior exhibits deterioration mostly due to surface damage which in turns affects on the intimate contact of the junction.

Sheet resistance likewise the type of electrical conductivity was measured using four-point probe technique. Conductivity type was maintained to be n-type before and after laser treatment indicated that the used laser energy is not high adequately to change the type of conductivity.

The variation of sheet resistance with laser energy density is described in Figure (4). Sheet resistance was increased from 0.46 Ω/أ (the as-received sheet resistance) to 1.55 Ω/أ after irradiation with 5.92 J.cm^{-2} laser energy density, but it is diminished to a value smaller than its initial value, e.g, 0.11 Ω/ أ after irradiation with high laser energy density (21.1 J/cm^2).

The above mentioned can be interpreted as following: after laser irradiation, phase transformation is taken place and amorphous phase will be produced leading to increase sheet resistance. On the other side, increasing laser energy density will reduce the segregated impurities that are created previously during diffusion [8] and hence, will contribute in increasing doping concentration. Consequently, sheet resistance will be decreased. Another observation can be caught from this figure that is at high laser energy densities (>11.34 J.cm^{-2}) sheet resistance displays a steadiness which supports that there is no more segregated impurities that can be diffused [2].

Table (2) shows reverse saturation current (I_{St}) and Schottky barrier height (Φ_{Bn}) that were extracted from the semi-log forward I-V curve (not found here) by using the following equation:

$$\phi_{Bn} = \frac{kT}{q}\ln\left(\frac{A^{**}T^2}{J_{St}}\right) \qquad (1)$$

where kT/q is the volt equivalent of temperature, A** is Richardson constant, and J_{St} is a saturation current density.

Increase of the saturation current with laser energy density is undoubtedly because of the increment of interface states density.

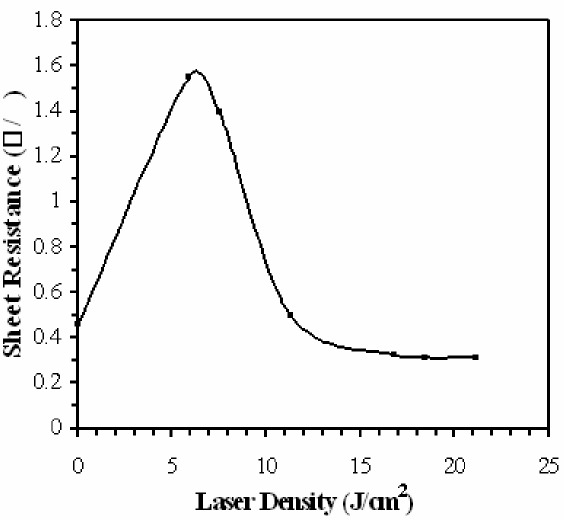

Fig. (4). Sheet resistance as a function of laser energy density.

According to this result, downfall in barrier height will be expected. Schottky barrier height exhibits a soft decrease with increasing energy density. Barrier decreasing is a definite indicator of improving ohmic contact. A 0.28 eV of barrier was obtained at 21.1 J.cm^{-2} laser conditions, which gives fair agreement with theoretical considerations of best ohmic contacts.

Table (2). Influence of laser energy density on I_S and Φ_{Bn}.

E_d (J/cm^2)	I_S (μA)	Φ_{Bn} (eV)
5.92	4	0.31
11.34	20	0.32
16.8	50	0.30
18.4	90	0.29
21.1	200	0.28

Specific contact resistance (R_C) that calculated from the following equation describes the electrode resistance hence; it is calculated from Φ_B that formerly determined.

$$Rc = \frac{k}{eTA^*}\exp\left(\frac{e\phi_{Bn}}{kT}\right) \qquad (2)$$

Figure (5) demonstrates the variation of R_C with different laser conditions. The figure shows sharp decrease of R_C with increase laser energy density. Comparing the results of R_C for contacts of unirradiated silicon (6.4 $\Omega.cm^2$) with the results for contacts of irradiated silicon (e.g. 1.9 x 10^{-4} $\Omega.cm^2$ at 21.1 $J.cm^{-2}$ laser condition) we can see a huge decrease in R_C for laser treated samples. This decrease refers to the feasibility of laser technique among other techniques to produce good ohmic contact. Barnes & Leamy [10] achieved low specific contact resistance (about 27 x 10^{-4} $\Omega.cm^2$) for contacts prepared by using transmission line model (T.L.M) technique.

Table (3) tabulates the lowest specific contact resistance that recognized by some workers and the current work. By making a comprehensive comparison between these results, one can deduce that Nd:YAG pulsed-laser surface treatment is a candidate method to produce best ohmic contact.

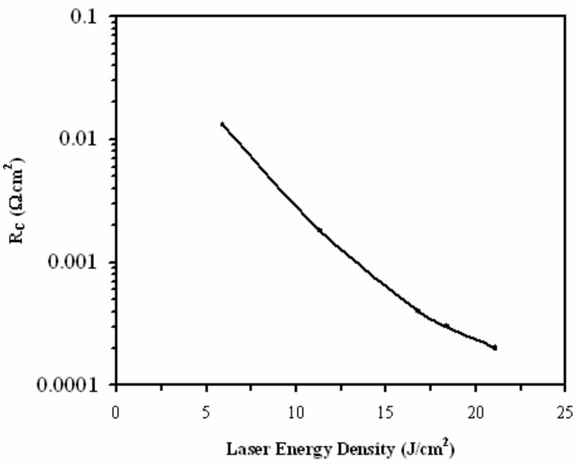

Fig. (5). Specific contact resistance as a function of E_d.

Table (3). Specific contact resistance for some MS contacts.

Semiconductor Properties			**Contact Material**	**R_C x 10^{-4} ($\Omega.cm^2$)**	**Reference**
Semiconductor Type	**Type of Conductivity**	**N_D x 10^{17} (cm^{-3})**			
Ge	n	0.3	Sn	25	[10]
Ge	p	0.8	Cd	35	[11]
Si	n	1.3	Sn	30	[8]
Si	p	23	In	23	[10]
GaAs	n	0.7	Te	8	[11]
GaP	p	1	Te	6	[8]
GaP	p	40	Zn	10	[10]
Si	n	22	In	1.9	Present

Conclusions

From what has been discussed above, one can conclude that Nd:YAG laser irradiation of n-Si surface facilitates the obtainment of ohmic contact with In-electrode. Near-unity rectification factor can be obtained at certain energy density of laser irradiation. Results of specific contact resistance approve that this technique is a competitive as compared with conventional techniques.

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إنتاج اتصالات أومية ذات مقاومة واطئة على السليكون المانح بوساطة الاحتثاث بالليزر

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الخلاصة

في هذا البحث ، تمت دراسة إمكانية إنتاج اتصالات أومية شبه مثالية وبكفاءة لاتصال In/n-Si بوساطة ليزر نيديميوم–ياك النبضي وبأمد نبضة 300 µs. جرى استخدام عدة كثافات طاقة ليزرية، وقد تم تحديد أفضل كثافة طاقة التي تعطي أفضل النتائج . وقد تم مناقشة طبوغرافية السطوح المشععة بشكل مستفيض لتحديد ظروف السطح التي تلعب الدور المهم في التأثير على نوعية الاتصال ، وقد دعمت التفسيرات بالصور الفوتوغرافية. إن قياسات تيار–جهد في الانحيازين الأمامي والعكسي كذلك ارتفاع الحاجز تم دراستها للنماذج المشععة بالليزر. إن إجراء مقارنة بين نتائج هذا البحث والنتائج المنشورة أثبتت أن هذه النتائج توافق الاتصال الأومي القياسي، وإن مقاومة الاتصال النوعي ذات القيمة (1.9×10^{-4} Ω.cm^2) قد تم الحصول عليها للنماذج المشععة بطاقة 21.1 J.cm^{-2} وهي أقل قيمة مسجلة لحد الآن لاتصال In/n-Si .