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Application of laser driven fast high density plasma blocks for ion implantation

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Abstract

The measurement of very narrow high density plasma blocks of high ion energy from targets irradiated with ps-TW laser pulses based on a new skin depth interaction process is an ideal tool for application of ion implantation in materials, especially of silicon, GaAs, or conducting polymers, for micro-electronics as well as for low cost solar cells. A further application is for ion sources in accelerators with most specifications of many orders of magnitudes advances against classical ion sources. We report on near band gap generation of defects by implantation of ions as measured by optical absorption spectra. A further connection is given for studying the particle beam transforming of n-type semiconductors into p-type and vice versa as known from sub-threshold particle beams. The advantage consists in the use of avoiding aggressive or rare chemical materials when using the beam techniques for industrial applications.

Keywords: Application to nanotechnology; Block acceleration of particles by lasers; Intense electron beams; Intense ion beams; Laser ion source; Skin layer acceleration

1. NONLINEAR FORCE LASER DRIVEN FAST PLASMA BLOCKS AS NEW ION SOURCE

The measurement by Badziak *et al.* (1999) of the drastic difference of ion emission from laser irradiated plasma by ps-TW laser pulses, compared with all the former known MeV ion generation, provides a basically new scheme for ion generation for application of laser driven ion sources (Sharkov *et al.*, 1996) for accelerators (Haseroth & Hora, 1996; Thomas, 2004), as well as for ion implantation (Boody *et al.*, 1996). The new effect was understood as a skin layer mechanism in contrast to usually occurring relativistic self-focusing being avoided by very clean (very high contrast ratio) laser pulses (Hora *et al.*, 2002*a*, 2002*b*; Badziak *et al.*, 2004*a*, 2004*b*). It was clarified before that the usual MeV ion generation of highly charged high current ion emission from laser produced plasma was by more than five orders of magnitude better than all the classical ion sources (Hora *et al.*, 2002*b*) where the space charge limitation due to Langmuir-Child law limited the electron and ion emission to several ten mA/cm^2 while the laser produced plasma arrived at more than 10^5 A/cm^2. In both cases, the highly charged ions were emitted under wide spread angles. The electron emission at laser irradiation on solids (Siller *et al.*, 1972) with emission current densities being more than a million times higher than the Langmuir-Child limit is based on the same nonlinear force and self-focusing mechanisms, and is of the same category for applications and advanced industrial techniques. A new access to these techniques is reported here with the following experiments together with detailed explanations of the new aspects.

The self-focusing process was essential for the very high current and high energy ions emitted from the laser produced plasma. This all happens at laser powers above MW as measured in 1962 by Linlor (see Hora, 1991). The fact that the highly charged ions have energies separated linear on their charge number Z excludes a thermal mechanism and the large number of the ions (up to 10^{15}) and excludes that the Z-separation is the thermal ambipolar mechanism

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(less than 10^9 ions). The observation of Linlor and others induced the studies of the essentially nonlinear processes in laser produced plasmas leading to the first generalization (Hora *et al.*, 1967) of the ponderomotive force to the dielectric properties of plasma expressed then by the general nonlinear force (Hora, 1969*b*, 1991) after it was first the merit of Weibel (1957) that he generalized the pre-Maxwellian ponderomotive force of electrostatics (electrostriction) to the high frequency electromagnetic field interaction with electrons in vacuum.

A necessary condition for the measured keV and more energetic ions was the derivation of ponderomotive self-focusing (Hora, 1969*a*; Palmer, 1971; Shearer & Eddleman, 1973; Chen, 1974) with the threshold of about MW laser power to understand the nonlinear anomalies of laser-plasma interaction. The mechanisms is that a filament is produced with more than 10^{13} W/cm^2 intensity, even with few MW laser pulses as directly seen by Richardson and Alcock (1971) from which the 30 keV electrons of 10^4 A/cm^2 current densities were measured (Hora, 1991) against the Langmuir-Child law and where the keV ions were coming from. It is remarkable that the measurements of vacuum discharges changed from their initial space charge limitation (Gisela Eckhard, 1970, private communication, Hughes Aircraft Lab., Malibu) to ion emission above the Langmuir-Child law due to the discovery of a channel generation in the emitting solid during the high voltage vacuum discharge (Bilek, 2001). The angular spread of the emitted ions was similar to the laser ion source which produces much higher currents and much higher ionization Z of the ions.

Self-focusing was later (Hora, 1975) extended to relativistic conditions at laser intensities above 10^{15} W/cm^2 resulting in MeV to GeV (Haseroth & Hora, 1996) ions with ionization Z above 60. The first MeV ions from carbon were reported by Ehler (1975) where 90% of the laser energy went into the MeV ions, while there was a second group of fast ions with Z-separation observed apart from a slow group of thermal ions. The second fast group (Woryna *et al.*, 2000) could be correlated with the hot (X-ray) temperature of the ions (Haseroth & Hora, 1996) as derived by Gitomer *et al.* (1986) where the high laser intensity caused a thermalization of the quivering electrons measured by the X-rays followed by the hot electron ambipolar acceleration similar to the theory of Wilks *et al.* (2001). The fit of the thermalization for this Gitomer mechanism of the second fastest ion group was possible only if the quantum deviation of the collision frequency was included (Haseroth & Hora, 1996: Sction 5; Hora *et al.*, 2002*a*: see Section 3). The number of ions due to the double layer Debye-sheat acceleration of about 10^{12} agrees with the measurements.

In contrast to this summarized situation on ion sources and laser produced ion generation, we underline that a further drastic improvement of the otherwise well advanced laser ion source is the new nonlinear force driven Skin Layer Acceleration (SLA) (Hora, 1969*a*, 1969*b*; Badziak *et al.*, 2004*a*, 2004*b*) produces ion current densities above 10^{10} A/cm. The emitted ions have the theoretically predicted (Hora, 2003) and experimentally confirmed (Badziak *et al.*, 2004*a*, 2004*b*, 2005) very narrow emission angle in contrast to all other mentioned ion sources.

It has to be underlined that the block generation by the nonlinear force driven SLA is essentially based on avoiding relativistic self focusing (Hora *et al.*, 2002*a*, 2002*b*; Badziak *et al.*, 2004*a*, 2004*b*, 2005) where density rippling processes and their suppression are important (Hora, 1991: Figs. 10.10 and 10.11; Hoffmann *et al.*, 1990; Purohit *et al.*, 2003; Saini & Gill, 2004; Jablonski *et al.*, 2005; Glowacz *et al.*, 2006), as the result of partial standing waves where the nonlinear (ponderomotive) forces pushes plasma faster to the nodes than the other plasma dynamics could straighten the motion. The theory (Hora & Aydin, 1992) confirmed this mechanism and how this could be overcome by laser beam smoothing, especially by broad band irradiation (Hora & Aydin, 1992, 1999; Osman *et al.*, 2004*a*, 2004*b*). The following approach is specifically directed to apply new developments of the plasma block generation (Hora *et al.*, 2002*a* or *b*; Badziak *et al.*, 2004*a*, 2004*b*) for next developments of ion generation for beam implantation where the difference between the block acceleration scheme (Hora, 2004; Osman *et al.*, 2004*a*, 2004*b*) to the option of fast ignition (Bauer, 2003; Deutsch, 2004; Mulser & Bauer, 2004; Mulser & Schneider, 2004; Doria *et al.*, 2004; Osman *et al.*, 2004*a*, 2004*b*; Ramirez *et al.*, 2004; Hoffmann *et al.*, 2005; Badziak *et al.*, 2005) for laser fusion plays a similar role.

2. APPLICATION TO ION IMPLANTATION

Implantation of ions energies above 100 keV into solids is a common technique to change the properties of the irradiated target. For these purposes, all kinds of acceleration techniques for the ions are applied where the source of the ions is based on classical mechanisms, but the laser driven ion sources are of interest despite their expensive equipment because they provide an enormously higher gain (Sharkov & Hora, 1996). Some points of the laser ions source for ion implantation were considered by Boody *et al.* (1996) including the modification of the strengths and increasing the hardness of metal surfaces, or the reduction of dry friction of steel by implanting ions (Zheng *et al.*, 1989). Reduction of friction by up to a factor of ten was measured. Even the miraculous property was reported that during the abrasion of the hardened iron surface, it happens that the ions seem to move further into the steel. The improvement of surface properties of polymers by particle beam irradiation should be mentioned.

The broad stream of ion implantation in the semiconductor industry and research with single crystals or amorphous silicon or GaAs was initiated when it was measured (Shockley, 1976) that the insufficiencies of doping semiconductor crystals, e.g., silicon, by diffusion of V or III elements by not achieving the desired plane junctions were caused by linear or two dimensional lattice defects along which the diffusion was much faster than in the bulk crystal. The desire was then to fire the doping ions into the crystal. This indeed resulted in better geometric distributions for the junction layers, but it was realized that the implanted ions were at interstitial positions between the macromolecular diamond lattices of the semiconductor. To move the implanted ions, to substitute lattice positions, annealing at about 800°C for hours were necessary. It was then considered that the implantation current density had to be at such high levels that the implantation had to produce the high temperatures during the implantation that the rearrangements with the crystal lattice structure were performed in one step. Apart from other problems arising from solid state physics, the necessary high current densities for the implanted ions up to nearly MeV energy could only be provided by laser-ion sources.

It has to be mentioned that implantation of nitrogen into silicon with 600 kV accelerators only for the rather low concentrations of doping for p-n-junctions damaged the basic lattice very strongly. This could be seen from the fact that the otherwise high thermal conduction of the homopolar silicon crystals was decreased by a factor of 30 (Goldsmid *et al*., 1984), after the strength of the stress was evaluated using a quantum theory of the compressibility (Hora, 1983).

Measurements using laser ion sources for implantation were performed (Doria *et al*., 2004) where mostly the advantages of iodine lasers were studied. These applications are still to be extended in order to find the conditions for industrial use.

3. MEASUREMENTS OF NEAR BAND-GAP DEFECTS

In preparation to study the plasma block generation for an ion source or similar effects, experiments with electron beams were performed. A number of initial experiments are reported along the lines of earlier interaction studies. An initiation of the generation of changing properties by beam irradiation was seen in the example for the severe distortion of a poly-crystalline structure of silicon by 75 keV intense electron beam irradiation (Hora, 1961). Since the evaporated silicon layers for subsequent electron beam irradiations were thinner than the electron penetration according to the Whiddington law, a nearly uniform change of the poly-crystalline silicon was possible. It was well-known that irradiation in silicon produces all kinds of defects as seen from the change of the optical transmission spectra for longer weave lengths, than the otherwise not changeable fundamental band absorption. The thin layers, however, permitted the observation that even the fundamental band absorption was shifted by 0.1 to 0.2 eV (Hora, 1961) when the intense 75 eV electrons produced stress in the layers close to their brattling off (Fig. 1), obviously causing the widening of the lattice by Freckle defects by an increase of the specific volume by up to 10% (Hora, 1983) with the well known reduction of the thermal conductivity (Goldsmid *et al*., 1984).

Experiments with thicker layers could not show—if any—a shift in the fundamental absorption since this was overcast

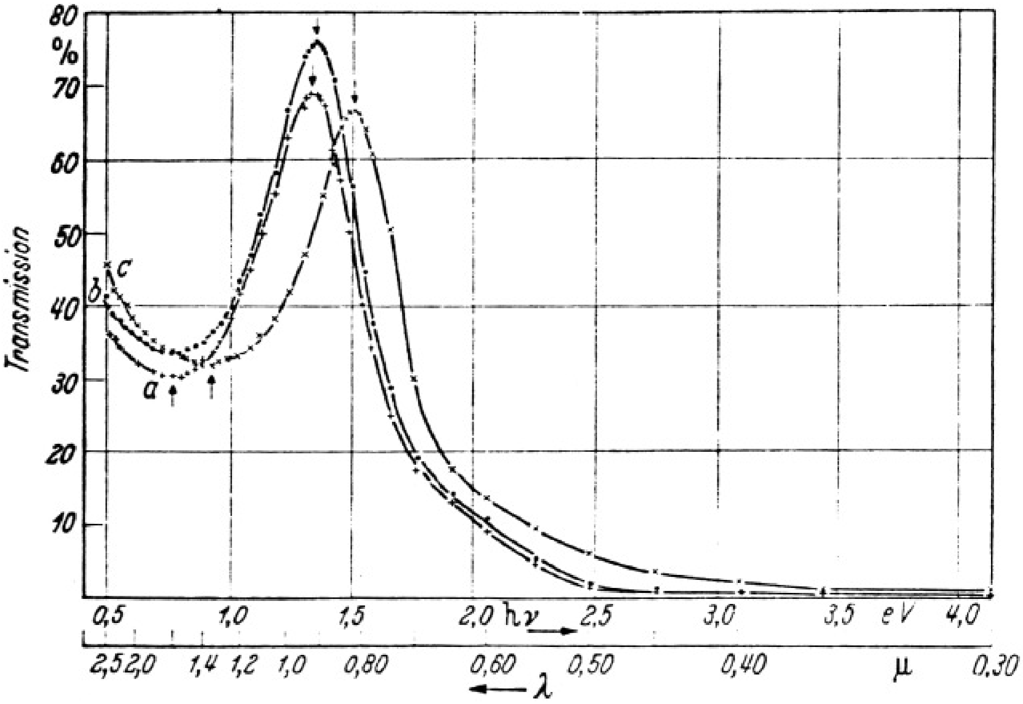

Fig. 1. Absorption spectra of thin evaporated silicon layers before and after bombardment with intense 75 keV electron beams (Hora, 1961) showing that the fundamental band absorption was shifted by 0.2 eV: (**a**) without irradiation, (**b**) at soft irradiation, (**c**) at strong irradiation (Hora, 1961).

by the bulk material into which the interacting beams did not penetrate. But the generation of defects with energy levels just below the fundamental band gap was observed (Sari *et al*., 2004) as an indication of the strong damage produced in the irradiated semiconductors. In this experiment, bombarded samples were n-type silicon single crystal with (110) orientation which mechanically and chemically were polished.

A concave cold cathode electron gun with obstructed discharge mechanism was used. Figure 2 shows a schematic view of the electron gun. The obstructed discharge in low operating gas pressure produces a monochromatic beam owing to little interactions of electrons with neutrals. The apparatus is shown in Figure 3. The spot size current and energy of electron beam were 1 cm^2, 10 mA, 25 keV, respectively. Samples were bombarded at doses in the range of 10^{16} to 10^{19} electrons/cm^2. A Varian, Cary 500 spectrophotometer was used to measure the optical properties of the samples before and after electron irradiation. The reflection measurement performed at shorter wavelength using SR accessory (Fig. 4). Transmission curves and its dependencies on the wave lengths (Fig. 5) confirming that we have created structural defects close to the fundamental band gap absorption (shorter than 1000 nm wave length) which may be due to tangling bonds. We also can compare the amount of curve shifting at increasing dose. With increasing the dose the amount of shifting enhances.

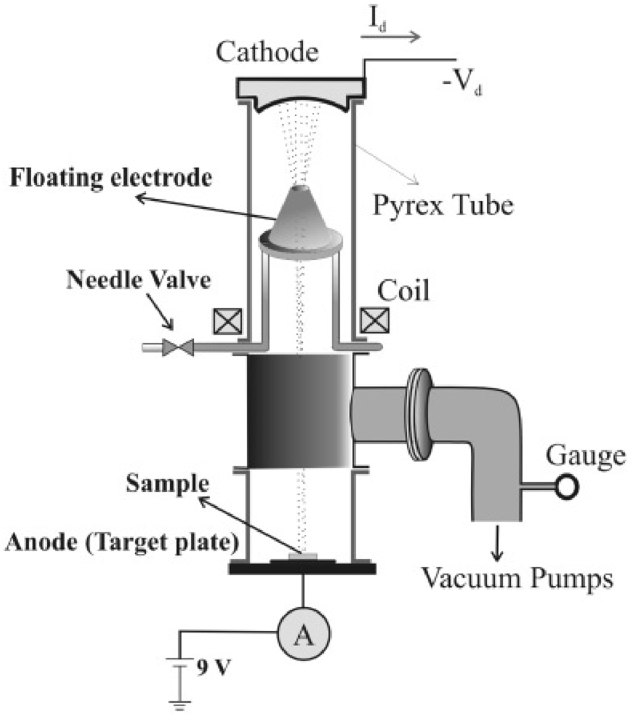

Fig. 2. Schematic structure of the electron gun with a concave cathode.

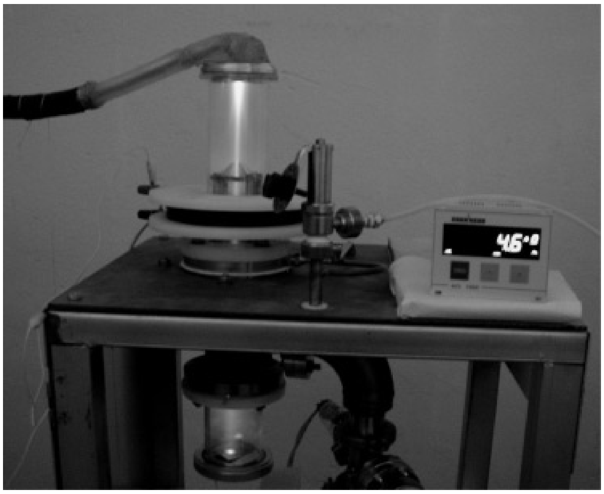

Fig. 3. Constructed electron gun facility in an experiment.

4. BEAM PRODUCED NON-CHEMICAL TRANSFORMATION OF N-TYPE TO P-TYPE SEMICONDUCTORS

Following the optical results, the program to use the irradiation of semiconductor single crystals or polymers by particle beams produced by the advanced laser ion sources, is aiming non-chemical and purely particle irradiation treatment especially using the plasma blocks from nonlinear force driven SLA. This may lead to an alternative way to produce p-n-junctions for diodes, solar cells, and polar transistors possibly down to nanometer dimensions.

The first results of this kind were known from electron bombardment on silicon single crystals, Figure 5 (Hora,

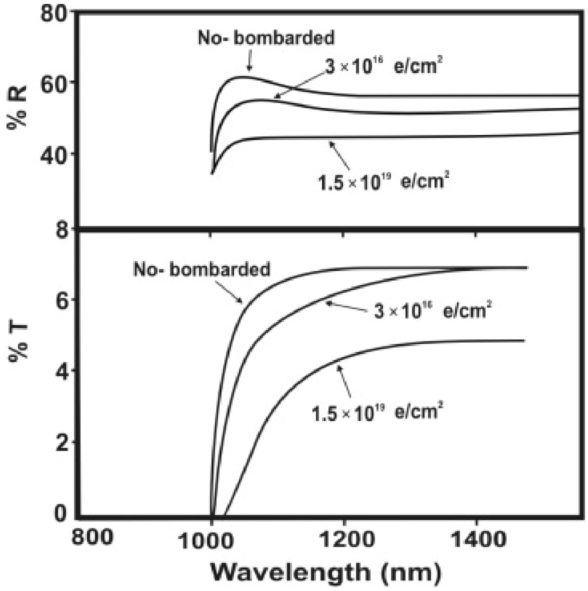

Fig. 4. Measurement of reflection and transmission versus wavelength for no-bombarded and electron bombarded n-silicon at different doses.

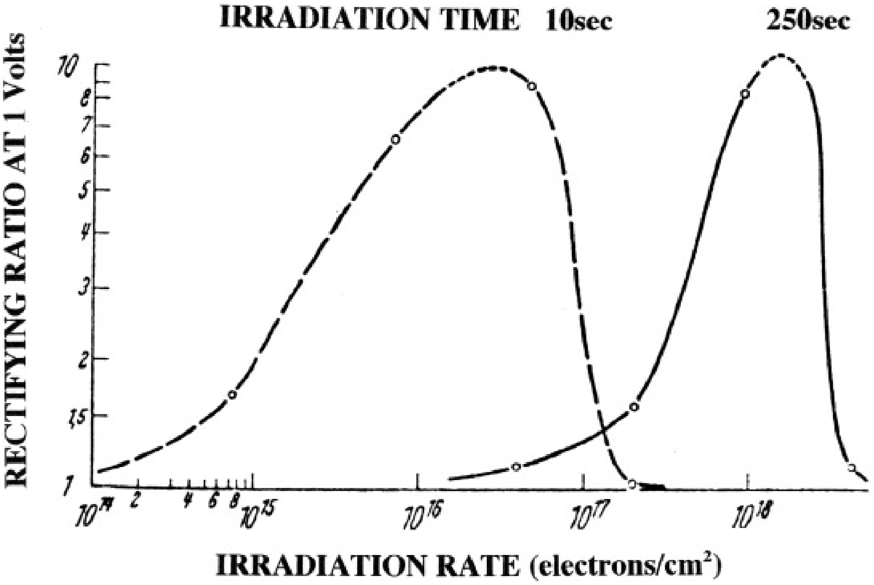

Fig. 5. Rectifying ratio of silicon after 75 keV electron bombardment of varying irradiation rate (dose) with pulse of different irradiation time measured from n-silicon voltage-current characteristics using barrier free contacts (Hora, 1962).

1962). It was known before (Lark-Horowitz, 1957) that a change of n-conducting silicon into p-conducting silicon by electron bombardments was possible by irradiating the crystal with electron about 200 keV. This electron energy was necessary to confer the necessary collision energy to the heavy silicon atom when being bound within the diamond lattice for removal, and to shift into an interstitial position (Schottky defect). One of the four bounds to the former neighbor atoms is then tangling and produces p-conduction. It was then unexpected that very intense electron beams of 75 keV energy were achieving the same change from n- into p-conduction (Hora, 1962) which measurement is reproduced in Figure 5. The bombardment with much lower doses did not show any change and the rectification increased with increasing doses at constant interaction times until a maximum was reached and decrease then to zero rectification at very high doses. Repeating this experiment with longer interaction times showed that the maximum rectification needed a higher dose while reaching zero rectification at very high doses. The dependence of the rectification maximum on the irradiation time was measured what indicated that the process may have been linked to a temperature, especially the bleaching out of rectification at higher dose where the target temperature at interaction was the highest.

This discovery of the subthreshold change of n- into p-conductivity of silicon (Hora, 1962) was initially not accepted by the Lark-Horowitz group where measurements were claiming that the reported process n- into p-conductivity does not take place at all. Other measurements (Zaikovskaya *et al.*, 1970; Kreutz, 1976) fully reproduced the subthreshold change of the silicon as well as further experiments (Vavilov *et al.*, 1975) and as summarized later in view of the further knowledge of particle bombardment on semiconductors (Hinckley *et al.*, 1979). The question was then what is the mechanism for the change from n- into the p-conductivity. Since the energy of the electrons was definitely too low to produce the removal of a silicon atom from a lattice position, it was discussed (Zaikovskaya *et al.*, 1970) whether the intense electron bombardment produces plasma to the well known high energy of up to 10 eV which subsequent interaction with the silicon atoms produces the n- to p-change. This may well be a process which needs further consideration while the before mentioned thermal reduction of the rectification at very high irradiation doses may have indicated a kind of annealing process as known from the standard treatment of silicon after implantation of 500 keV nitrogen ions (Hora, 1983). It could be speculated that the 75 keV electrons may open individual bonds between silicon atoms which tangling state generates holes while letting the silicon atom still in its crystal position however with keeping bonds to the other neighbor atoms.

The new interest in the subthreshold n- to p-transition in semiconductors is of interest again since the electron beam bombardment can be concentrated to smaller sizes than the optical wave length which is the lower limit for the size of rectifiers and transistors in micro-electronics (Fig. 6). Using electron beams could develop much more toward nanotechnology and much higher density of electronic elements on silicon chips. The first question to be studied also in view of the ion implantation processes (Boody *et al.*, 1996) finally using the SLA processes, is to clarify the nature of the subthreshold defect generation and to confirm that this is sufficiently stable against overheating of the microelectronic elements. For microelectronics the advantage is the possibility to reduce the size of the elements (Benstetter *et al.*, 2002), while the advantage to produce solar cells from

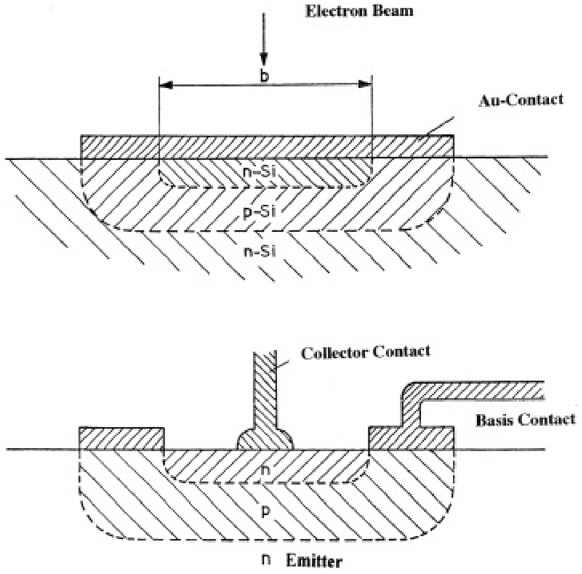

Fig. 6. Procedure for polar transistor production on a nanoscale. First a p-Si is produced (upper part) under the conditions of highest possible rectification (see Fig. 2) against the n-Si chip followed by a shorter range high temperature treatment to return to n-Si simultaneously with evaporation of the gold contact in the range b due to the electron beam. Finally the collector contact is added for the npn transistor (Benstetter *et al.*, 2002).

conducting n-polymers by electron beams generating p-n-junctions (Hora, 1976) is in the fact that this is possible without huge amounts of very aggressive chemicals in case of mass production.

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