Study of the Density Angular Distribution of the Atomic Hydrogen Flow Produced by the Source Based on Low-Pressure Arc Discharge with a Small-Diameter Emission Orifice

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Abstract – Laws of formation of low-energy large area hydrogen atoms beam generating by a gas-discharge source with an emission orifice of small diameter (0.5–2 mm) are investigated. It is shown, that at distance from the source equal 285 mm diameter of atoms beam is 200 mm. Two modes of the source functioning, described by various angular distribution of atomic hydrogen flow density are found out. In the mode with a plasma jet effusing in vacuum, the nonuniform beam with a maximum which is being in paraxial of a beam area is formed. In the mode when the output of plasma from a discharge cell is minimized, rather homogeneous beam is formed. Atoms flow intensity decreases with increase distance from the source in inversely as the square of distance. Angular distribution of flow density of neutral atoms poorly depends on a discharge current and gas flow rate.

1. Introduction

Fast reduction of the technology node of integrated circuit and development of nano-electronics stimulate development of new technologies, allowing to obtain atomically clean, atomically smooth semiconductor surface with high structural perfection. Processing of semiconductor structures by means of neutral chemically reactive particles beams is considered as one of such perspective technologies [1], and cleaning of semiconductor materials surface in hydrogen atoms flow is today one of the demanded methods of surface preparation [2, 3]. Development of similar technologies demands development of effective control methods of neutral radicals flow density, and also methods of formation and transportation of homogeneous intensive large area beams. However these, actual today problems are for the present far from final solution. Therefore the works directed on studying of laws and mechanisms of formation of intensive large area hydrogen atoms beam, represent significant interest, both with scientific, and from the practical point of view. The present work is devoted to studying of formation of large area hydrogen atoms beam generating by the point type gas-discharge source.

2. Experimental techniques

Object of research was the atomic hydrogen source on the basis of low-pressure gas discharge with the self-heated cathode and small diameter emission orifice [4], installed in the vacuum chamber which is evacuated by the turbo-molecular pump. Residual atmosphere pressure in the vacuum chamber was $1...4 \cdot 10^{-4}$ Pa. The image of source, the scheme of discharge cell and the experiment scheme are presented on Fig. 1. A direct current discharge was initiated in the cell after introduce in it of the purified molecular hydrogen with the gas flow rate 3–60 sccm. AH beam effused through the emission orifice 4 with diameter 0.5–2 mm in the cathode-reflector 1 and, expanding in transportation space, exposed set of AH sensors 3, located on a radial, concerning the axis, line (Fig. 1, *c*). Thin-film AH sensors (8 pieces) allowed to measure of atoms flow density in a mixed atom-molecular flow of particles in the range from $5 \cdot 10^{13}$ up to $5 \cdot 10^{15}$ at. $cm^{-2} \cdot s^{-1}$ [5]. Sensors were fixed in the flat holder 2 at distance 15 mm from each other. Data from sensors were read out by means of the eight-channel automated system and transmitted into computer. After processing experimental data by the method presented in work [5], distributions of AH flow density to radius across the beam were drawn. Angular distribution of AH flow density obtained after additional mathematical processing initial data, thus it was considered, that AH flow falls on each sensor under changing angle φ, and distance between source and sensor s increases in process of removal of sensors from axis of the source (increase in radius r).

3. Results and discussion

In Fig. 2 distributions of AH flow density on the beam cross-section, and in Fig. 3 angular distributions of AH flow density for various distances h from the emission orifice of AH source up to the axial sensor are resulted. It is visible, that in process of increase h diameter of a relative homogeneous beam part increases and at h=285 mm is 200 mm, that is enough for processing silicon wafers of the corresponding diameter.

As the flow is formed by the point type source, it is necessary to expect, that distribution of AH flow density across the beam will be described by the cosine law. Really, each atom born in gas discharge pla-

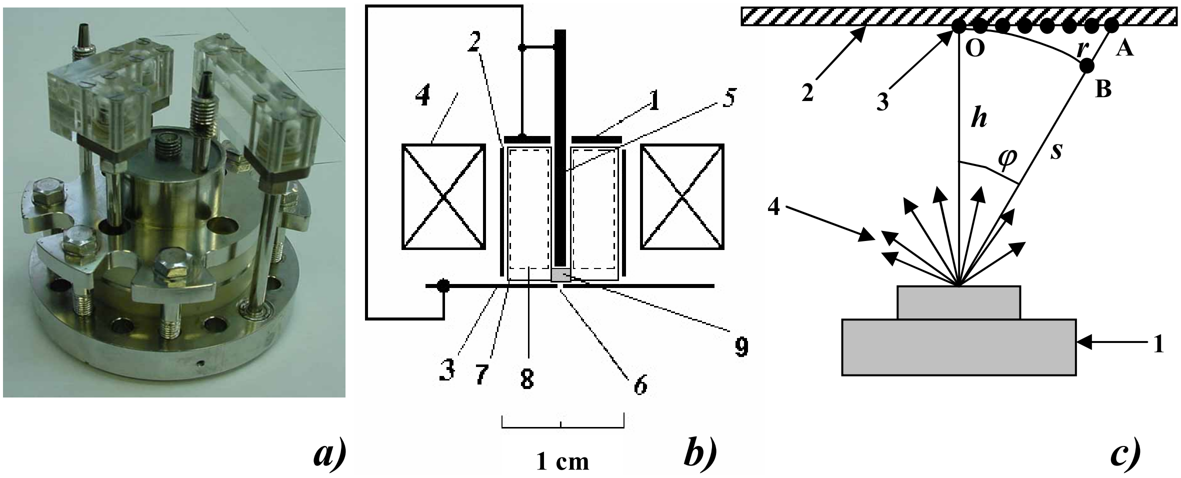

Fig. 1. Image of AH source (a), scheme of discharge cell electrodes (b): 1, 3 – cathodes-reflectors, 2 – anode, 4 – permanrnt magnet, 5 – self-heated cathode, 6 – emission orifice, 7 – area of reflective discharge (continuous line), 8 – area of magnetron discharge with the heated cathode (dashed line), 9 – area of arc Penning discharge (grey area) and experiment scheme: 1 – AH source, 2 – AH sensors holder, 3 – AH sensor, 4 – emission orifice of the AH source and AH flow

sma as a result of a dissociation by electronic impact, has equal probability of movement in any direction (in spatial angle 2π), that should lead to formation of distribution of AH flow density described by the cosine law.

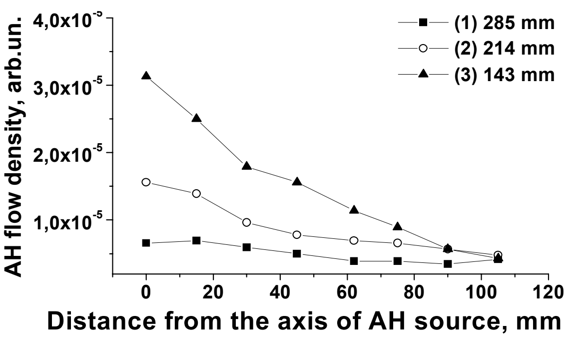

Fig. 2. Distributions of AH flow density on a beam section for various distances source -sensor (operating mode of AH source: *Ip*=2 A, *Up*=212 V, P_H=1·10⁻² Pa)

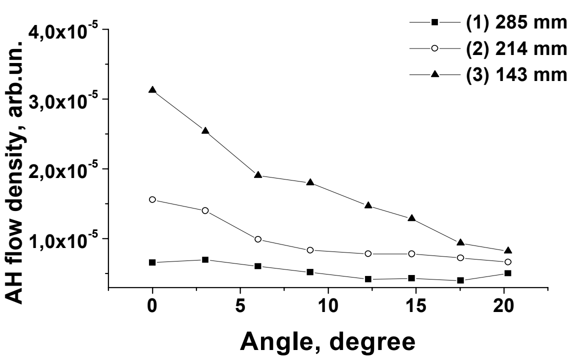

Fig. 3. Angular distribution of AH flow density for various distances source-sensor (operating mode of AH source: *Ip*=2 A, *Up*=212 V, P_H=1·10⁻² Pa)

Experimental check has shown, that this assumption not completely corresponds to the validity. In Fig. 4, a two basic types of distributions of flow density across the beam which are formed by the source on the basis of low pressure arc discharge are shown. The first type of distribution under the form is closer to the distribution described by the cosine law (curve 2). The second type of distribution (curve 1) was significantly differs from the first type: for it stronger angular dependence is characteristic.

Transition from one type of distribution to another occurs at change of AH source operating mode. The first type of distribution is obtained in the source operating mode with a plasma jet effusing in vacuum, the second type – in the mode when a plasma output from the discharge cell is minimized. In Fig. 4, the operating mode of AH source with a plasma jet is shown. It is visible, that a jet is sharply directed, has diameter less than 1 cm and length nearby 10 cm. It is possible to assume, that increase in AH flow density at axes (in angle ≅10°) is directly connected with additional atoms generation in a plasma jet, due to hydrogen molecules dissociation by high-energy electrons, oscillating in a jet. It is obvious, that each atom born in a jet, has equal probability of the directed movement in a spatial angle 2π, i.e. for each atom there is no preferable direction of movement. However that fact, that a jet is a expanded atoms source which has the form of strongly extended cylinder, leads to that AH flow density in the greatest degree increases in a paraxial direction (in angle ≅10°).

Considering point character of the source, it is necessary to assume, that the atoms flow density should decrease with increase distance from the source proportionally $1/s^2$. The executed measurements have shown, that for r <90 mm the flow density magnitude really decreases inversely as the square of distance from the source. However for r=90–105 mm are observed deviations from this law. Change of AH flow density with increase distance h not so considerably as it would be possible to expect according to the law $1/s^2$ (Fig. 2, 3). It is possible to assume, that the observable situation is connected with the contribution of the atoms reflected from vacuum chamber walls. Considering, that the recombination coefficient of hydrogen atoms in molecules on a real metal surface usually has magnitude close to 0.1 [6], each atom can do to ten impacts with vacuum chamber walls before the recombination. It is obvious, that at constant atoms flow from the source in the vacuum chamber some equilibrium concentration of "uniformly" distributed atoms will be established. This background concentration also can be the factor responsible for a deviation from the law $1/s^2$ for higher s at which density of the flows primary and reflected from walls become commensurable.

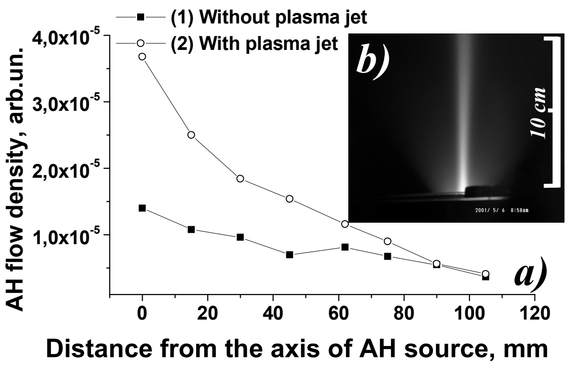

Fig. 4. Distributions of AH flow density depending at distance from the axis of AH source (a); image of AH source in an operating mode with plasma jet, a side view (b)

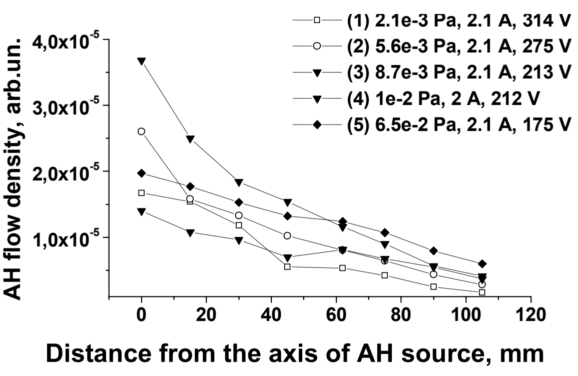

Fig. 5. Distribution of AH flow density on a beam section for various gas flow rate

Results of research of effect of the gas flow rate and discharge current on uniformity of atoms beam distribution are resulted in Fig. 5, 6. It is visible, that the form of distribution of neutral atoms poorly depends on a discharge current and the gas flow rate. It is known, that change of these parameters leads to significant change of plasma concentration and, hence, to changes of AH concentration in discharge and integrated density of effusing AH flow. The executed experiences have shown, that change of the gas flow rate and a discharge current do not render significant effect on the form of area from which there is a output of atoms, and do not influence the law of selection of atoms in a beam, as allows to keep the form of distribution. However it is necessary to note, that dependence of the integrated flow on a discharge current is linear, at increase in a discharge current from 0.5 up to 2 A the integrated flow increases in 2.5 times. While dependence of the integrated flow on a gas flow rate has nonlinear character (Fig. 7), that is caused by change of a operating mode of AH source about which it was spoken above. That fact is interesting, that at increase in a gas flow rate from 10 up to 65 sccm the integrated flow does not change, thus discharge voltage decreases with 212 V up to 175 V (~20 %).

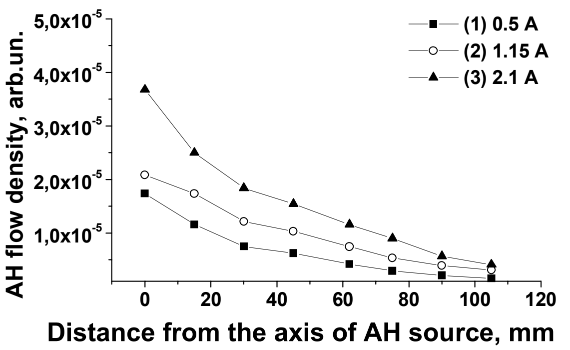

Fig. 6. Distributions of AH flow density on a beam section for various discharge currents

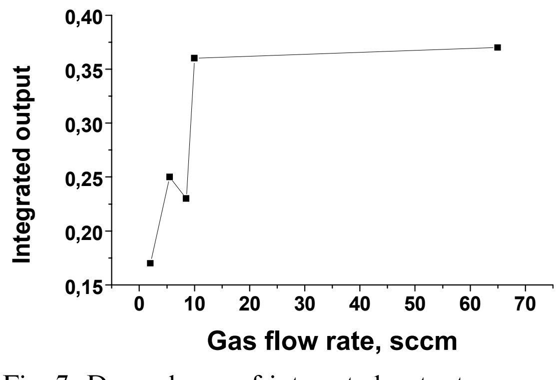

Fig. 7. Dependence of integrated output versus gas flow rate

Weak dependence of the form of distribution of AH flow density on a discharge current and a gas flow rate is the important fact opening wide technological opportunities on control of AH flow intensity and hydrogen pressure in a zone of a semiconductor wafer processing without change of the form of distribution of a flow density on a beam section.

4. Conclusions

Laws of formation of the large-area hydrogen atoms beam generated by a gas-discharge source with the small diameter emission orifice (≅0.5–2 mm) are investigated. On removal from the source equal 285 mm diameter of a homogeneous part of atoms beam is ≅200 mm. Two operating modes of the source, described by various angular distribution of atomic hydrogen flow density are found out. Change of a discharge current and a gas flow rate practically does not render effect on the form of distribution of a flow density on a beam section that opens wide technological opportunities on control of parameters of atoms beam with preservation of its uniformity. The beam with such parameters can be used in technological processes of industrial semiconductor wafers processing in diameter of 200 mm.

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