RELATIVE CONTRIBUTION OF VOLUME AND SURFACE-PLASMA GENERATION OF NEGATIVE IONS IN GAS DISCHARGES

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Abstract

Surface-plasma generation of extracted H^- ions in gas discharges without the addition of cesium is analyzed. At the present time, it is common consensus that surface-plasma generation of extracted H^- ions dominates above volume processes in discharges with the admixture of cesium or other catalysts with low ionization potential. We will present evidence that surface-plasma generation can be enhanced in high density discharges without cesium after electrode activation by high temperature conditioning in the discharge. The diffusion of impurities with low ionization potential is the presumed cause of the observed H^- emission enhancement. For the effective generation of H^- ion beams in discharges without cesium, it is necessary to optimize surface-plasma generation of extracted H^- ions. Such optimization allows considerable improvement of H^-/D^- sources characteristics.

INTRODUCTION

The problem of intense, high brightness negative ion beam production for accelerators and for neutral beam injection was solved by small admixture of cesium vapor into a gas discharge ion source [1]. In the following experiments [2-4] it was demonstrated that cesium adsorbtion decreases surface work function and catalyses surface plasma generation of negative ions (SPG), enhances secondary emission of negative ions caused by the interaction of plasma with electrode surface. Ion sources based on this process have been named Surface-Plasma negative ions Sources (SPS). It is important, that cesium admixture significantly decreases the current of co-extracted electrons.

A small admixture of cesium vapour in gas discharge improves H^- production significantly. But using cesium is complicated the ion source operation and requires a careful stabilization of cesium injection and discharge parameters. There were a lot of attempts to develop H^- sources with acceptable H^- beam parameters but without cesium [5-8]. The intent was to improve volume generation (VG) of extracted H^- ions. Volume generation is caused by electron collision with molecules in the plasma volume. Dissociative electron attachment with resulting H^- formation increases significantly in collisions with vibrationally/ rotationally excited molecules. In old plasma sources the highest intensity of H^- was below 5 mA and the current of co-extracted electron was tens of times larger [9]. Volume generation of H^- was improved in tandem multicusp sources by separate generation of vibrationally/rotationally excited molecules in driver volume with high electron temperature and generation of H^- in filter volume with low electron temperature. Emission current density of volume sources was limited by the necessity to have high molecular density and high electron density for volume H^- generation. The typical emission current density of volume sources was up to 20 mA/cm^2, and current was ~15 mA, and the current of co-extracted electrons was ~ 20-30 times larger.

SPG ACTIVATION IN GAS DISCHARGES

By empirical optimization in some sources, H^- current with acceptable emittance was increased up to 40-50 mA and the ratio of electron current to H^- current was decreased down to 4 without cesium admixture. These enhancements of H^- generation were comparable with effect of cesium catalysis. Understanding the reasons of these improvements is important for H^- sources upgrading. The enhancement of SPG in discharges without cesium was discussed in report [10]. Below we will discuss possible reasons of these improvements.

In KEK/ JAERI tandem multicusp source [11] the increase of H^- current from 14 to 38 mA was reached by high temperature activation of source electrodes by discharge after optimization of plasma electrode configuration for anode surface plasma generation of H^-. For plasma generation, pulsed discharge with LaB_6 direct heated cathode was used. In this case the enhancement of anode SPG in discharge without cesium addition was clearly demonstrated. Earlier, the increase of H^- emission current density up to 0.75 A/cm^2 was produced in flat magnetron/planotron ion source without cesium by electrode activation in high dense discharge [12]. In the energy spectrum of negative ions, cathode surface plasma generated H^- ions were observed. For a higher discharge current, anode SPG must be the dominant mechanism of H^- generation. After cesium admixture into this source, the emission current density was increased up to 3.7 A/cm^2. As discussed in [10], enhanced anode SPG was observed in some other negative ion sources with high dense discharges in crossed fields: in the Ehler's type source [13] and more clearly in the Ehler's source with insulated plasma electrode [14]; in the Dudnikov type source with LaB_6 cathodes [15, 16]; in the source with a tubular magnetron discharge in longitudinal magnetic field [17]; in duoplasmatron with tubular discharge [9].

Cesium adsorption lowers the surface work function, and this increases the probability of sputtered and reflected particles to escape in the form of negative ions. This probability increases with the work function decrease and the increase of velocity of particles moving away from the electrode surface. The theory of negative ionization of particles at interaction with an electrode surface has been developed in works [18, 19]. Calculated

probability of H^- formation as the function of initial particle velocity for a different work functions and as the function of work function for different initial velocities are shown in Fig.1. Experimental and extrapolated dependence of H- formation on the surface work function is shown in Fig.2 from [20]. A visible increase of secondary emission of H^- (up to ~10^{-2}) can be achieved by the decrease of surface work function down to ~2.5 eV, corresponded the deposition of Li, Mg, Ba, La. The emission of negative ions increases with the increase of negative potential of the electrode contacting with plasma, because the energy and intensity of positive ions bombarding the electrode surface increases, the quantity of the sputtered and reflected particles increases, and so does the velocity of their movement away from the electrode surface. The potential drop near the electrode accelerates emitted negative ions without a space charge limitation. It also increases the free path of ions in plasma without destruction and allows their extracting through the emission aperture. Cesium is locked on the surface of the negative electrode as it comes back from plasma in the form of ions. Electrode surfaces with the potential close to the potential of plasma are also bombarded by fast plasma particles and emit negative ions. The efficiency of negative ion generation on these electrode surfaces is lower than on electrodes with negative potential, but can be high enough.

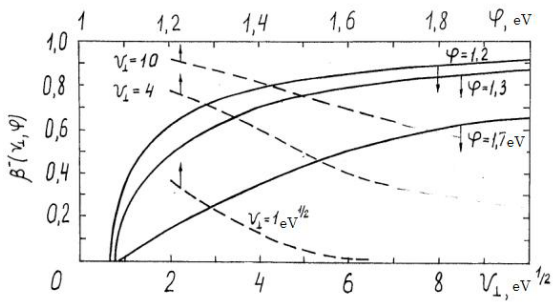

Figure 1: Negative ionization coefficient as function of starting velocity and work function from [2].

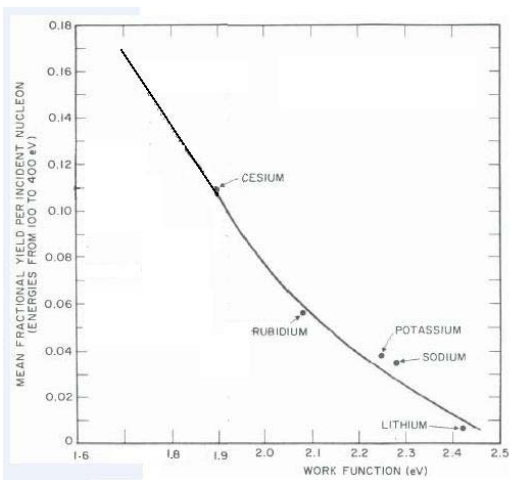

Figure 2: Experimental and extrapolated secondary emission yield for surfaces with different work functions.

The conditions for volume and surface-plasma generation of H^- in gas discharges coexist. However, the relative contribution of VG and SPG in the emission of H^- and in the support of volume H^- density can be very different. In discharges with high emission current density the free path of cold H^- is very short (~1 mm). In these conditions, the volume density of H^- is determined by VG. But the production of emitted H^- is determined by SPG on the plasma electrode surface around the emission aperture. To enhance the efficiency of the emitted H^- production, it is necessary to optimize SPG on the plasma electrode. This can be achieved by the efficient transformation of gas molecules to a flux of hyperthermal atoms with the energy of several eV. It is necessary to use a magnetic filter with a strong magnetic field for strong suppression of electron diffusion to the emission surface. It is useful to use a slit extraction system. It is necessary to optimize the shape and thermal property of the plasma electrode for the efficient extraction of generated H^- ions. It is essential to use the activation of the emission surface by discharge and by thermo processing. After such optimization, it is possible to produce a high density of H^- with much lower density of electrons on the emission surface, and to suppress the ratio of electron current to H^- current γ down to less than 5-10 in discharges without cesium. A high efficiency of such optimization was demonstrated in [11,12]. The emission current density of H^- ion was increased up to ~1 A/cm^2 in discharges without cesium. The most probable reason for this secondary emission enhancement is the diffusion of an impurity with a low ionization potential from the bulk of the electrode to the surface and sputtering from RF antenna coating. Refractory metals such as Mo, W, Ta used for cathodes fabrication have relatively high concentration of alkaline metals [27], mainly sodium and potassium, because for the production of these metals such compounds as Na_2WO_4, K_2TaF_7, are used. In experimental measurements, presented in [20-22] the secondary emission of D^- was increased up to 50 times by the deposition of sodium and potassium on the copper surface (work function φ was decreased from 4.8 eV down to 2.25 eV) and up to 100 times by the deposition of cesium (φ was decreased from 4.8 eV down to 1.9 eV).

A further decrease of the work function of plasma electrode emission surface by an optimal deposition of cesium and activation (φ down to ~1.6 eV) increases H^- /D^- emission up to 4-5 times relative to the discharge with activated electrodes without cesium and decreases electron emission below H^- emission.

An efficient generation of H^-, without cesium, is achieved in multicusp filament discharge source for the cyclotrons at TRIUMF [23] producing 15 mA and electron to H^- ratio ~4. Similar H^- source is under development in CIAE, China [24].

RF sources use a few turn helical or plane spiral antenna to drive plasma confined in a multi-cusp magnet arrangement. Driven at low RF frequencies – 2 MHz is the most common – dense plasma is formed, that can generate a high density of vibrationally/rotationally exited

hydrogen molecules. Towards the extraction area, a filter dipole reflects high energy electrons, and conditions are optimized for the volume generation of negative ions in the filter area with dissociative attachment of cold electrons. A collar around this low electron temperature region (containing cesium on the SNS source) increases the yield of surface plasma generated H^-. Without cesium, the SNS RF source has produced 15 mA of H^-, but with unacceptably high current of co-extracted electrons.

The DESY external antenna source [26] has now delivered a low *df* beam ~38/0.05 mA, 150 μs length pulses of H^- at 8 Hz, without cesium enhancement, using an RF power of 20 kW. The performance of the source is presently limited in current, pulse length and duty factor by the RF power supply, cooling and very high current of co-extracted electrons (I_e/I-=γ~35). Recently H^- current was increased up to 60 mA with electron current of ~2 A.

The source designed by Seoul University [25] uses RF at 13.56 MHz delivered with a flat spiral antenna behind a quartz or alumina window. This allows the antenna to be completely separated from the plasma. Used in CW operation, the source manages to deliver 0.2 mA of H^- at 20 keV with no cesium. Previously, higher currents were claimed but the previous measurements appear not to have fully suppressed the electron current.

The variation of source performance with frequency in the range from 1.65 to 8 MHz, was recently investigated at DESY [26]. The multi-cusp field configuration was kept constant, but the number of antenna windings was varied, using 6.5, 20 and 40 turns. The highest ion current is obtained with 2 MHz and 6.5 windings.

CONCLUSION

The lifetime of SPS is limited by an electrode (cathode) sputtering and flake formation. In tandem ion sources without the use of cesium, the energy efficiency and gas efficiency are low. In addition, without cesium admixture, the discharge voltage and current are high and there is a high current of co-extracted electrons. These strong destruction factors limit the duty factor and source lifetime. Large-volume tandem sources with the arc and RF discharges, tubular discharge magnetron sources, compact SPS (such as the magnetron, Penning discharge SPS, and the semiplanotron) without cesium can be used for the production of H^- beam for accelerators with current up to 30 mA, but with low (0.1%) *df*. With low gas efficiency, the pumping speed must be very high and the cost of vacuum pumps will be significant.

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