HIGH DEUTERIUM CONCENTRATION IN PALLADIUM FOR APPLICATION TO COLD FUSION

Han S. Uhm and W. M. Lee

Naval Surface Warfare Center

10903 New Hampshire Ave., White Oak

Silver Spring, Maryland 20903-5000, U. S. A.

Based on theoretical calculations, new schemes to increase deuterium density in palladium over its initial value is presented. High deuterium concentration in palladium is needed for application to the solid-state fusion. The first deuterium enrichment scheme makes use of the plasma ion implantation, which consists of a cylindrical palladium rod (target) preloaded with deuterium atoms, coated with diffusion-barrier material and immersed in a deuterium plasma. The second deuterium enrichment scheme makes use of the temperature gradient effects on the deuterium solubility in palladium. A heat source at temperature T_2 and a heat sink at temperature T_1 (where $T_2 > T_1$) are in contact with two different parts of a palladium sample, which has been presoaked with deuterium atoms and has been coated with diffusion-barrier material or securely locked in a metal case.

INTRODUCTION

When the atomic ratio γ of deuterium to palladium is considerably higher than unity, a substantial fraction of the palladium volume will be transformed into PdD_2 crystal, where the nearest-neighbor distance between deuterium atoms is d = 0.94 angstrom.[1] These deuterium atoms are located in a potential well created by the neighboring palladium atoms, executing oscillations with their fundamental oscillation amplitude λ = 0.1 angstrom. According to a recent calculation by Schwinger,[2] the D-D fusion cross section increases by a factor of 10^7 when the parameter d/λ changes from the natural value of $d/\lambda = 9.4$ to 7.52. Apparently, the fusion cross section depends

very sensitively on the vibration parameter d/λ of the oscillation. A slight decrease in the vibration parameter tremendously increases the fusion cross section, which is with a measurable range. In this regard, we propose two schemes to increase deuterium density inside a palladium rod by making use of plasma ion implantation[3,4] and temperature gradient effects.[4,5] Achieving a high concentration of deuterium atoms inside palladium is also an interesting subjects for basic electrochemical studies and for researches on hydrogen in metals.

PLASMA-ION IMPLANTATION SCHEME

Shown in Fig. 1 is a schematic presentation of a proposed experiment for deuterium enrichment inside palladium. A cylindrical palladium rod with radius a and coated with a diffusion-barrier material is immersed in a deuterium plasma which is contained by a grounded cylindrical chamber. The plasma with a density ranging from 10^9 cm^{-3} to 10^{12} cm^{-3} and with electron temperature ranging from 2 eV to 10 eV is generated by either RF or glow discharge or by thermionic filaments.[6] The palladium rod (target) is connected to a high-power modulator, which provides a series of 1 - 10 µs negative pulses with voltage V_0 ranging from 10 kV to 200 kV. The palladium rod may be initially soaked with deuterium atoms outside the chamber by a non-plasma method before coating with the diffusion-barrier material. The atomic ratio (γ = D/Pd) of deuterium to palladium in a deuterium soaked palladium rod can easily reach 0.6 without any pressurization.[7] During the application of negative pulses to the target, deuterium ions will penetrate the diffusion-barrier coating to be implanted inside the rod. A prolonged implantation of deuterium ions will increases the deuterium concentration inside the palladium over the initial atomic ratio γ = 0.6. The ion beam power deposited on the surface of the palladium rod is a tremendous heat source, which must be removed by a cooling system.
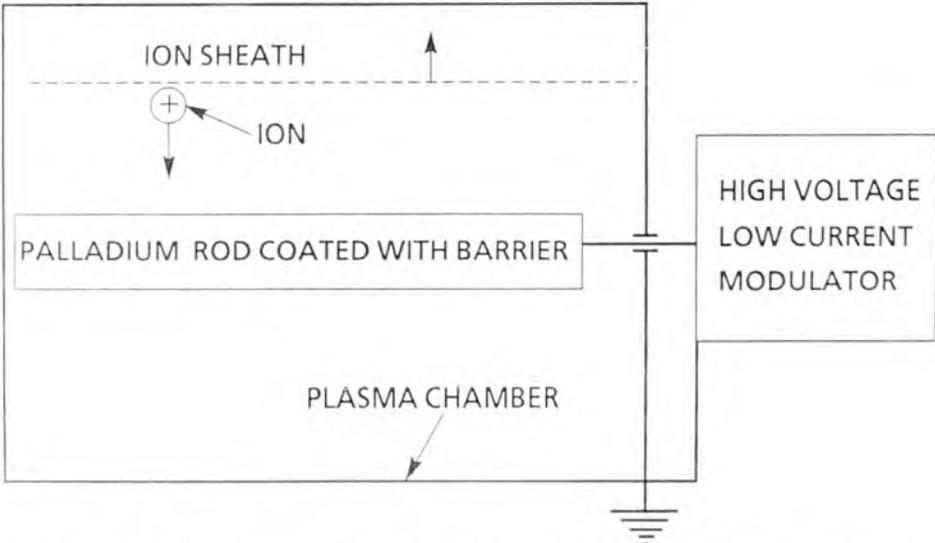

Fig. 1. Schematic presentation of the proposed plasma-ion implantation.

During this negative pulse, electrons are repelled from the target on the time scale of the electron plasma frequency, leaving behind an ion sheath. The ion sheath further expands in time as the negative-voltage pulse is sustained and the ions uncovered by the sheath bombard the target, penetrate through the diffusion-barrier coating and accumulate in palladium. The dynamics of the ion sheath has been studied extensively.[8] During the negative-voltage pulse, the ion sheath radius increases. The final radius R at the end of the negative-voltage pulse is determined in terms of the plasma density n_p, the pulse length τ and the applied voltage V_0. The ion current I_{peak} during the pulse is approximately expressed as

$$I_{peak} \sim \frac{\pi e n_p L}{\tau} R^2,\tag{1}$$

where L is the length of the palladium rod. The average ion current I is given by

$$I \sim I_{peak} \tau H,\tag{2}$$

where H represents the number of the negative-voltage pulses per second. It is shown that a good candidate for the barrier material is an alloy of 60 percent iron (Fe) and 40 percent nickel (Ni) in weight, whose diffusion constant and solubility are much less than those for palladium. There could be other materials which perform as a better diffusion barrier. A desirable thickness of the barrier coating should be less than 10^3 angstroms.

Prolonged implantation of deuterium ions will increase the deuterium concentration over the initial density $n_0 = 4 \times 10^{22} \, cm^{-3}$, which can be easily attainable even without pressurization. In a high-pressure environment of deuterium gas, the initial density can be higher than the above value. Increase of the deuterium density over its initial value is evaluated and is expressed in terms of diffusion coefficient and thickness of the barrier material. A deuterium density profile inside the palladium rod is also calculated, by making use of the rate equation and diffusion properties of deuterium atoms in palladium. Due to the small diffusion coefficient, the incoming ions do not diffuse quickly, thereby accumulating near the target surface. Assuming an applied voltage, $V_0 = 100$ kV; plasma density, $n_p = 5 \times 10^9 \, cm^{-3}$, pulse duration, $\tau = 1 \, \mu s$, and pulse repetition rate, $H = 10^5 \, s^{-1}$, we found that the average ion current coming into the target is $I = 0.4$ ampere for a target size with radius a = 1 cm and length L = 10 cm. Assuming an iron-nickel alloy barrier with its thickness of 10^3 angstroms, the deuterium saturation density is calculated to be $\xi = 3 \times 10^{23} \, cm^{-3}$, which is five times higher than the palladium atomic number density. For a reasonable target size, the deuterium density in palladium can triple its original value within a few days of ion implantation time.

A heat source at temperature T_2 and a heat sink at temperature T_1 ($T_2 > T_1$) are in contact with two different parts of a palladium sample, which has been presoaked with deuterium atoms and coated with diffusion-barrier material, thereby creating a temperature gradient in the sample [Fig. 2]. Based on previous studies,[9] we assume that the solubility $S(p,T)$ is an increasing function of the pressure p and a decreasing function of the temperature T, due to exothermicity associated with palladium-hydrogen bonding. That is, in general,

$$\frac{\partial}{\partial p} S(p,T) > 0, \qquad \frac{\partial}{\partial T} S(p,T) < 0. \tag{3}$$

Thus the deuterium atoms in the hot region are forced to migrate into the cold region due to the solubility difference between the regions. This migration results in a highly concentrated deuterium density in the cold region.
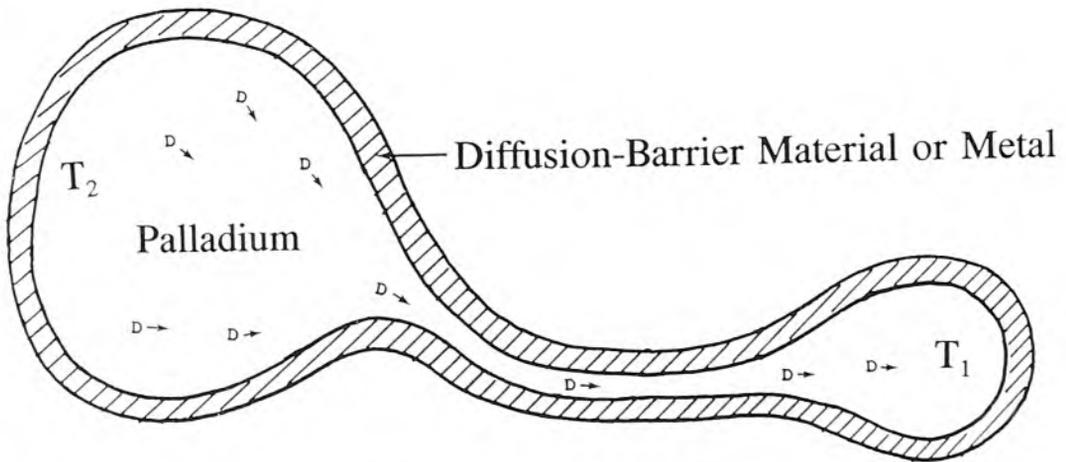

Fig. 2. Deuterium migration from a hot to cold region in palladium sample.

Since the total number of deuterium atoms in the rod is fixed during the migration, the local solubility $S(n,T)$ must be a direct manifestation of the local deuterium density. The local solubility of deuterium in this situation is not yet fully understood. The detailed properties of the local solubility $S(n,T)$ of deuterium, including the irreversible thermodynamic process, are currently under investigation by authors and will be presented elsewhere. The deuterium density in the steady-state condition is therefore expressed as

$$n(T) - \frac{S(n,T)}{S_0} n_0, \tag{4}$$

which must satisfy the conservation of the deuterium-atom number; i.e.,

$$[\frac{\partial}{\partial u} n(x,t)]_A - 0,$$ (5)

where $(\partial/\partial u)n$ represents the derivation of the density with respect to the direction perpendicular to surface A of the palladium rod. Note that the solubility S_0 and the density n_0 denote their values before the temperature gradient is established. Once the temperature gradient is established, the deuterium atoms start to migrate from the hot region to the cold region, and the density profile will eventually settle into the steady-state value. It was found that the deuterium density in the steady-state condition is described in terms of the ratio S_2/S_1 of the solubility in the hot region to that of the cold region. The deuterium density concentrated in the cold region can be a few times more than its initial value for a reasonably small value of the ratio S_2/S_1. This scheme is particularly advantageous over other methods for compressing deuterium density in a small region because of a wide range of temperature windows, that can be applied to the palladium sample.

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