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Calculation of the generator for induction discharge initiation

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The upgraded RF generator operating at 880 kHz in wide ranges of radio-frequency power and gas pressure has been developed. The resonant circuits of the generator are calculated at 880 kHz. Real and imaginary components of the discharge system impedance versus the electron density are under consideration for the cylindrical inductively coupled plasma.

Keywords: RF generator, cylindrical inductively coupled plasma, silicon tetrachloride.

Представлено модернізований ВЧ генератор для збудження індукційного розряду, що працює на частоті 880 кГц в широкій області високочастотних потужностей і тисків газу. Проведено розрахунок резонансних кіл генератора на частоті 880 кГц. Розглянуто залежність дійсної і уявної складової імпедансу розряду від концентрації електронів для циліндричного індукційного розряду.

Ключові слова: ВЧ генератор, циліндричний індукційний розряд, тетрахлорид кремнію.

Представлен модернизированный ВЧ генератор для возбуждения индукционного разряда, работающий на частоте 880 кГц в широкой области высокочастотных мощностей и давлений газа. Проведен расчет резонансных кругов генератора на частоте 880 кГц. Рассмотрена зависимость действительной и мнимой составляющей импеданса разряда от концентрации электронов для цилиндрического индукционного разряда.

Ключевые слова: ВЧ генератор, цилиндрический индукционный разряд, тетрахлорид кремния

Introduction

At present plasma chemical processes are widely used in the world. The developing of discharge exciting sources is a main issue in organization of plasma-chemical processes, which must satisfy the requirements of the plasma-chemical system energy balance, maintenance of required gas and electron temperature, discharge sustaining in the predetermined pressure range when the partial pressure of initial reagents and pumping rates of the reaction products are changing.

There are various sources of discharge excitation. The induction high-frequency systems possess some comparative advantages among them. The coaxial disposition of the reactor and inductor simplifies the calculations of energy characteristics of plasma-chemical systems. Furthermore, the inductor situated outside the reaction chamber can slightly reduce the contamination of a final product in comparison with other excitation sources in which the plasma discharge is in contact with the structural elements of the plasma-chemical equipment.

The RF induction plasma sources are continuously improving in the direction of increasing the discharge energy input, pulsing and continuous lasing of the output signal, changing the continuous lasing frequency and pulse interval frequency, and increasing the efficiency of plasma chemical facilities. The high-frequency power, fed into the discharge, is absorbed in the skin layer. Therefore, to increase the plasma chemical system efficiency, the high-frequency exciting field should be sufficient for the electromagnetic energy release from the almost entire volume of a plasmoid.

In the plasma-chemical processes the use of the non-equilibrium plasma, characterized by the high electron energy at a relatively low gas temperature, occupies a special place that allows one to carry out chemical reactions for producing a final product and inhibits the reverse reaction [1], and also provides a possibility of carrying out chemical reactions, forbidden by thermodynamics, in equilibrium conditions.

Using of RF generators operating in the frequency range of 0.46÷2.0 MHz for induction discharge excitation, calculated in [2], shows that by changing the operating frequency from 13.56 MHz to the frequency 2.0 MHz the inductor power voltage is decreased in 3 times.

In addition, the application of RF generators for excitation of induction discharges, operating at low frequencies, allows one to minimize the loss in the inductor, as well as, in the circuits connected to it, and significantly simplifies discharge diagnosis.

The aim of the present study was the design modification of the commercial generator VChI-63/044, and its matching with the reactor inductor to carry out plasma-chemical investigations on the hydrogen reduction of silicon tetrachloride in the low-temperature non-equilibrium plasma.

Results and discussion

1. Upgrading of the high-frequency generator VChI-63/044.

The RF frequency generator VChI-63/044 operating in the pulse-periodic mode was upgraded to reach a continuous wave lasing at a frequency of 880 kHz. Changeover of the RF frequency generator to the continuous lasing mode has been performed by making a replacement of an adjustable thyratron rectifier by a non-adjustable diode one that appreciably improved the reliability and stability of the generator power source. The stable performance of the generator under various magnitudes of output power in a wide range of load parameters was ensured by dividing the matching circuits and power adjustment circuit. Continuous adjustment of the generator output power was carried out by the variable-ratio autotransformer set up at the power source input. The upgraded generator scheme is shown in Fig 1.

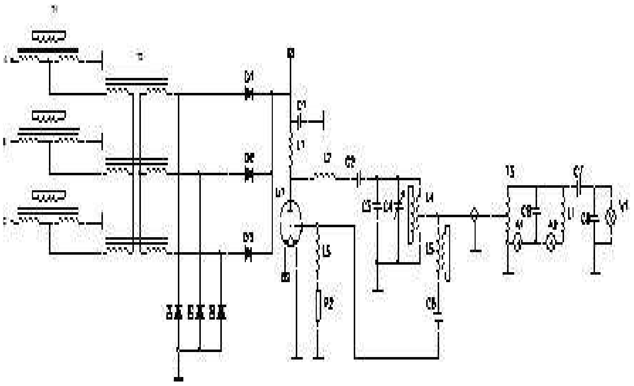

Fig.1. Schematic representation of the upgraded generator.

The generator is assembled on the GU-23-type lamp U1. Three-phase supply voltage of commercial frequency is fed via the adjustable autotransformer T1 of 25 kW, is increased by the high-voltage transformer T2 and then comes into the three-phase full-wave rectifier D1-D6. Each arm of the rectifier consists of twelve series-connected semiconductor diodes designed for the operational voltage of 1000V and 10A current and shunted by the 2W resistor with a resistance of 100 Ω.

The load circuit is formed by the inductor with an inductance of 6.5 μH and the capacitor C6 capacity of 5 nF. Harmonization of the generator with the load is carried out through the autotransformer T3. The autotransformer comprising 12 turns, of the 10 mm, copper pipe wound on the hull with diameter of 600 mm, has the inductance of 63 μH. The autotransformer design provides the step change of the turn ratio in the range from 0.08 to 1 by changing the number of turns in the primary circuit.

Measurements of voltage on the load circuit are carried out with the aid of a capacitance divider with a dividing coefficient of 1000:1. The current in the inductor and in the load circuit is measured with the aid of shielded Rogowski coils A1 and A2 respectively.

The parameters of the generator anode circuit were calculated by the framework of an equivalent circuit of the upgraded generator (Fig. 2), from the condition of resonance at the operating frequency and matching of the anode load equivalent resistance with a characteristic impedance of the cable. The coil with an average inductance value of 54 μH is used in the anode circuit of the generator. The anode circuit capacitance was calculated by the expression

$$C_A = \frac{1}{\omega^2 \cdot L_A}, \qquad (1)$$

where ω is the generator operating frequency, L_A is the coil inductance of the anode circuit.

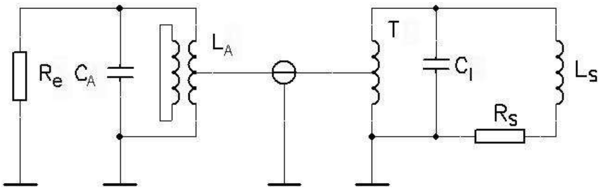

Fig.2. Equivalent circuit of the upgraded generator: R_e - the equivalent anode load resistance, L_A, C_A - anode circuit elements, T - matching autotransformer, C_l - capacitance of the load circuit, R_S - equivalent active resistance of the inductor with taken into account load influence, L_S - equivalent inductance of the inductor with taken in account load influence.

The estimated capacitance value for the frequency of 880 kHz is 606 pF. The plate circuit capacity is formed by both the capacitor battery of a fixed capacitance and the variable capacitor with a fluoroplastic dielectric of 20÷200 pF capacitance. The variable capacitor serves for fine resonance adjustment of the anode circuit.

The optimal value of the equivalent anode load resistance is determined from the expression:

$$R_e = \frac{U_{a\max}}{I_{a\max} \cdot a_1} - \frac{1}{S \cdot a_1}, \qquad (2)$$

where $U_{a\max}$ - maximum value of the anode voltage,

$I_{a\,max}$ - maximum value of the anode current, a_1 - fundamental harmonic ratio, S - mutual conductance of the lamp.

At $U_{a\,max}$=6.3 kV, the current value $I_{a\,max}$ with maximum power 25 kW equals 4A. The fundamental harmonic ratio a_1 at cutoff angle of 70° equal to 0,436, the mutual conductance of lamp GU - 23÷48,5 mA/V. The calculated optimal value of equivalent resistivity of the anode load is 3564 Ω.

The characteristic anode circuit impedance $\rho = \sqrt{\frac{L_A}{C_A}}$ for a frequency of 880 kHz is 300 Ω, and its Q-factor is $Q = \frac{R_e}{\rho} \approx 12$. In order to match the equivalent resistance of the anode load with a cable having a characteristic impedance of 50 Ω, the coefficient of cable connection into the anode circuit $n = \sqrt{\frac{\rho_c}{R_e}}$ is 0.12.

To ensure the required connection coefficient values in the structure of generator VChI -63/044 coils, additional outlets for cable connections are provided.

2.Estimation of the RF plasma discharge impact on the inductor impedance.

The improved RF generator was tested on the experimental assembly with a cylindrical quartz discharge chamber. The quartz tube, surrounded by the inductor, consist of 6.5 turns with an inductance of 7.36 μH and resistance of 0.03 Ω. The influence of high-frequency discharge plasma on the inductor impedance was estimated using the transformer model of an induction RF discharge [1]. In transformer model the inductor itself serves as a primary winding, and the plasma, generated in its inside, forms a secondary winding consisting of a single turn, the radius of which is determined by the high-frequency plasma discharge parameters. The transformer model is schematically represented in Fig. 3a.

The secondary winding of the transformer is characterized by the plasma resistance R_2 and inductivity L_2. The plasma turn inductivity includes two components: geometrical or magnetic inductance L_2, determined by the turn geometry, and inductivity L_e characterizing the electron inertial properties. The inertial induction L_e is the result of a complex nature of the RF discharge plasma conductivity and is determined by the relation:

$$L_e = \frac{R_2}{v_{eff}}. \tag{3}$$

where V_{eff} is the effective electron collision frequency.

In the pressure range under consideration the collisional mechanism of energy input into the plasma discharge is implemented, and the electron-neutral collision frequency significantly exceeds both the stochastic collision frequency and the electron-ion collision frequency, that makes it possible to equate V_{eff} to the electron-neutral collision frequency V_{en}.

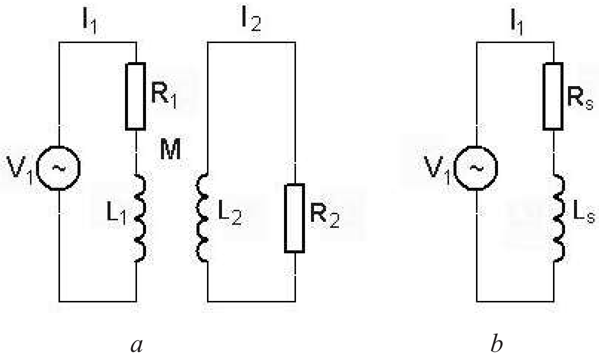

Fig.3. a) Transformer model of the high-frequency discharge. b) Equivalent circuit of the high-frequency discharge in the transformer mode.

For the pressure range where $\frac{\nu_{en}}{\omega} \geq 10$ and $\nu_{en} \geq 5{,}5 \cdot 10^7 s^{-1}$ the inductance L_e is much lesser than L_2, that allows us to neglect the L_e contribution into the inductor-plasma system impedance.

The inductances L_1 and L_2 are related by the mutual inductance M**.** The coupling coefficient *k* is determined by the relation:

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}} \tag{4}$$

The coupling coefficient *k* (0 <*k* <1) versus the electron concentration is shown in Fig. 4.

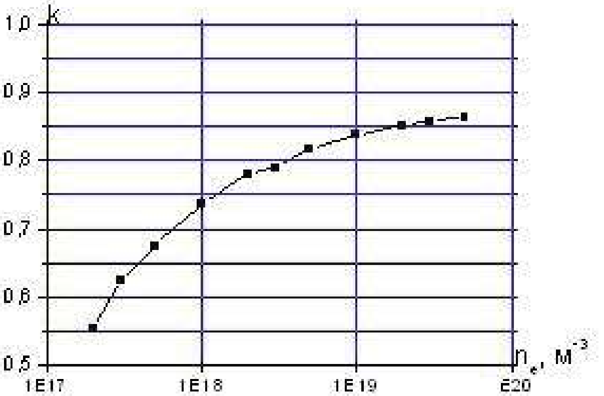

Fig. 4. Coupling coefficient *k* versus the electrons concentration.

The coefficient *k* monotonically increases with electron concentration increasing, asymptotically approaching to the theoretical maximum magnitude

$k = \frac{R^2}{B^2}$, where R is the discharge chamber radius, B is the inductor radius.

Applying Kirchhoff's second law to the primary and secondary transformer windings we obtain

$$V_1 = j\omega L_1 I_1 + I_1 R_1 - j\omega M I_2 \qquad (5)$$

$$V_2 = j\omega L_2 I_2 + I_2 R_2 \qquad (6)$$

Considering that $V_2 = j\omega M I_1$, after simple transformations of equations (3) and (4), the inductor-plasma system impedance reduced to the transformer primary winding can be determined.

$$Z = \frac{V_1}{I_1} = R_1 + \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} R_2 + \\ + j\left(\omega L_1 - \frac{\omega^2 M^2}{R_2^2 + \omega^2 L^2}\omega L_2\right) = R_s + jX_s \qquad (7)$$

The equivalent circuit of the inductive RF discharge transformer model is shown in Fig. 3b. The real and imaginary components of the impedance inductor-plasma system versus the plasma electron concentration $\frac{\nu_{en}}{\omega} = 10$ are shown in Fig. 5.

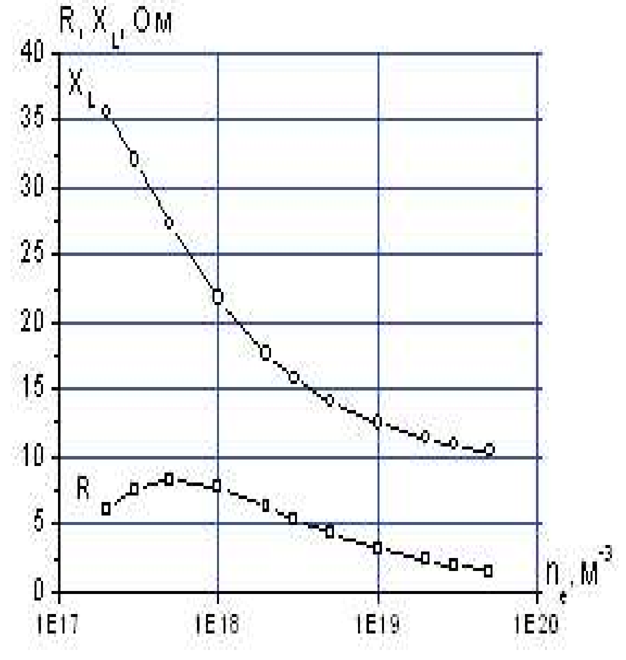

Fig.5. The real and imaginary components of the inductor-plasma system impedance versus the electron concentration for $\frac{\nu_{en}}{\omega} = 10$.

Assuming that the inputted induction RF discharge plasma power is absorbed in the skin layer of a depth δ, the plasma resistance can be determined from the expression

$$R_2 = \frac{2\pi \cdot r}{\sigma \cdot \delta \cdot h}, \qquad (8)$$

where σ is the real component of the complex conductivity of the high-frequency discharge plasma, δ - skin depth, h - discharge height, R - plasma turn radius equal to $r = R - \frac{\delta}{2}$ (R - discharge chamber radius).

The skin-layer depth is determined by the expression

$$\delta = \frac{c}{\omega_{pe}}\sqrt{\frac{2\nu_{eff}}{\omega}}, \qquad (9)$$

where c is the light speed, ω_{pe} is the electron plasma frequency.

The plasma turn inductance is calculated by the relation

$$L_2 = \frac{\mu_0 \pi r^2}{h}, \qquad (10)$$

where μ_0 is the magnetic constant.

The mutual inductance M is determined from the expression

$$M = \frac{\mu_0 \pi r^2 n}{h}, \qquad (11)$$

where n is the number of inductor turns.

It should be noted that by assessing the influence of the RF discharge plasma on the inductor impedance we have not considered the capacitive coupling between the inductor and the plasma, since at low frequencies it is not essential [3] and its influence on the inductor impedance can be disregarded.

In the model of the RF discharge transformer the generator power P_g can be considered as a sum of the power dissipated in the transformer primary winding (inductor) P_{in} and the power contributed to the plasma discharge P_d.

$$P_g = P_n + P_d = \frac{1}{2} I_1^2 (R_1 + R_2'), \qquad (12)$$

where I_1 is the inductor current amplitude, and $R_2 = \frac{w^2 M^2 R_2}{R_2^2 + w^2 L_2^2}$ is the reduced active plasma resistance of the transformer primary winding. The efficiency of power transmission from the inductor to the plasma is determined by the relation [4]

$$\eta = \frac{P_d}{P_{in} + P_d} = \left(1 + \frac{R_1}{R'_2}\right)^{-1} . \qquad (13)$$

From the relation (13) it follows that with a fixed value of R_1 the value of $R_2^{/}$ will be an indicator of the efficiency of energy contribution into the plasma discharge, namely, high values of $R_2^{/}$ correspond to high values of η and conversely. The impedance components of the inductor-plasma system (Fig.5) and the mutual coefficient *k* (Fig.4) versus the electron concentration, and, consequently, the RF power absorbed in the plasma, indicate to the existence of optimal energy contribution modes in the induction RF discharge. The energy efficiency is determined by the discharge configuration and depends on the type and pressure of the operating gas. As the gas pressure increases, an optimal energy input range is shifted towards higher electron concentrations.

The generator testing has shown its stable operation. A HF discharge, excited in molecular hydrogen and mixtures of hydrogen with chlorosilane, was observed in the pressure range of 15-250 Pa. The power density fed into the discharge was varying in the range from 1 to 7.2 W/cm^2.

Investigations on the plasma-chemical hydrogen reduction of silicon tetrachloride were carried out. The reaction of plasma-chemical reduction was conducted in the reaction chamber at pressure of 60 Pa with the ratio H_2SiCl_4=5:1 (flow rate for H_2 - 6.5 l/h, for $SiCl_4$ - 1.3 l/h.) The power density, fed into the discharge, was 6.5 W/cm^2.. Polycrystalline silicon films with a thickness of 8.5–11.6 µm were obtained for deposition time of 60-80 minutes. [5]

Conclusions

1. Experiments conducted with a upgraded RF generator has shown a stable operation at a power density, fed into the discharge of 1 to 7.2 W/cm^2 in the broad range of varying power load parameters.
2. Plasma-chemical hydrogen reduction of silicon tetrachloride in the low-temperature non-equilibrium plasma was carried out. Polycrystalline films with thickness of 8.5-11.6 µm were obtained.

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