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Instability and dynamic behavior of arc attachments on electrodes and the effect on electrode erosion

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Abstract: Plasma interacting with electrodes is one of the most challenging issues in many industrial applications, such as power-interruption and plasma-metal erosion. Because of the concentration of arc attachments (root) and the voltage drop across the plasma sheath layer, the arc roots consume great amount of energy, which subsequently will increase the local temperature and erode the electrodes. Due to the nonequilibrium condition at plasma sheath, it is very difficult to quantitatively estimate the arc root temperature profile. The recognition of arc roots behavior, like instability and pattern formation, is important to estimate the electrode erosion. The potential drop arising through the sheath (double layer) is nonuniform. Due to thermionic field emission, the strong flux of charge carriers through the sheath will cause instability of the double layer, which weakens the inner potential gradient. As a result, the strong current dependent potential drop features a negative resistance. The existence of negative resistance causes the instability of arc attachments in the forms of immobility and constriction. Their interdependence between local current density and potential drop gives rise to the arc root formation that concentrates the energy into a small spot. Owing to the negative resistance, any perturbation will cause the current density in the sheath to grow to approximately infinity or decay to vanish, namely arc root formation or extinction. Thereby, the arc root instability provides the basis for the dynamic behavior of arc attachments and detachments on the electrodes, which will help to understand electrode erosion and avoid the damage from the arc plasma in engineering applications.

Keywords: Voltage Drop; Negative Resistance; Gas discharge; Arc roots; Instability.

1. Introduction

The arc interacting on the electrodes is well studied for many engineering applications such as circuit breakers [1-8], plasma etching and welding [9-11], materials fabrication[12-18] and process the metal due to various kinds of damage. The arc root jumping is also frequently observed in arcs' propagation along the rail electrode's like in circuit breakers and plasma actuators . Some video recording the arc dynamics along a pair of vertical open-ended copper wires reveals a similar climbing phenomenon. The experimental observation of the travelling arc clearly illustrates the arc column gradually constricting into a small attachment point, namely the arc root. Existing literature states that the immobility of vacuum arc is restricted by metal evaporation and erosion, which entails arc root instability . When it comes to low-current arcs in air, the copper erosion happens trivially while the arc root hopping is very conspicuous.

Many studies have investigated the instability pertaining to arc attachment and detachment on the electrodes [23-25]. For example, nonlinear surface heating at cathode will account for the multiple modes of arc attachments, either diffusing mode or spot modes. On the anode side, the instability of electron overheating and evaporation-ionization are thought as the precondition for the formation of multiple arc attachments. Bistability of conduction states of gas discharge is experimentally demonstrated by the presence of an S-shaped negative resistance, which is explained by a combined effect of the self-assembly and decay of a space charge configuration in the double layer [23, 27, 28]. The double layer is conceptually referred to as the sheath, and normally consists of multiple layers that give rise to the voltage drop ΔV across it, obeying the relation $\Delta V \geq kT_e/e$, where T_e is the electron temperature, e is the electron charge and k is the Boltzmann constant. The potential drop is supposed to be decided by the sheath double layer formation, respectively. The double layer also exhibits instability that arises due to the injected beam of ions and electrons . For example, a weak density depression of charge carriers can lead to the formation of a strong potential drop . Therefore, many studies take advantage of this phenomena by defining a current density dependent potential drop across the sheath [7, 32, 33]. Huo et al proposed a spatial sheath layer featuring negative differential resistance, and initially apply this model into a magnetohydrodynamics simulation that clearly demonstrate the effect of nonlinear sheath layer on dynamic arc hopping.

Because of the collision/resistivity in the near electrodes' region, high current density j generates intensive heat on the order of $\sim j^2$. Thus, there is a consensus that thermally enhanced field emission and ion bombardment collectively liberate electrons from the cathode in a self-consistent manner. Since the plasma immediately adjacent to the electrode is not in thermal and ionization equilibrium[35, 36], the fully non-equilibrium arc plasma models should be employed for the charge transport and energy exchange between different particles in the sheath by considering two types of temperature [37-39]. However, the accurate prediction of electrons' and ions' temperature and their contribution to emission is still challenging. For example, the exact value is inconclusive, such as 10-30 volts[29, 33], 300 volts , temperature dependent or current density dependent values [3, 6, 7, 41, 42]. The space charge sheath is mostly implemented as a zero-dimensional interface by considering the energy balance[36, 38].

Actually, the nonlinear potential drop in the space charge sheath has a profound influence on the electric and magnetic field, as well as arc root profile. In this article, the negative resistance in potential drop curves is explained to understand the instability of dynamic arc attachment. Then, we propose an equivalent parallel circuit model to analyze the behavior of arc roots with negative resistance.

2. Results

Due to the thermionic field emission, the charge emission flux can change the double layer and attenuate the potential ramp, letting more current and generating more heat. Thus, the current flux and thermally enhanced emission can be mutually reinforced. This interaction causes a surge of local current density with the decrease of voltage drop across the sheath, as a kind of thermally induced instability. This kind of instability is deemed as the important factor for the attachment and detachment of dynamic arc roots on the electrode surface as observed in experiments.

For low-frequency plasma, the charge continuity equation will be recast into a reaction-diffusion form, which is always employed in the study of self-regulated pattern formation. The reaction-diffusion equation is in the forms of $\frac{\partial Y}{\partial t} = \nabla \cdot (D\nabla Y) + S(Y)$, in which D is the diffusivity, $\frac{\partial Y}{\partial t}$ represents the transient term, $\nabla \cdot (D\nabla Y)$ represents the diffusion term and $S(Y)$ represents the source term. If $S(Y)$ can be expanded as a function of the variable Y, namely $S(Y) = \mu Y + \alpha|Y|^2 Y + o(Y)$, this equation is of the Ginzburg-Landau type, which describes the evolution of physical variables with a bifurcation property.

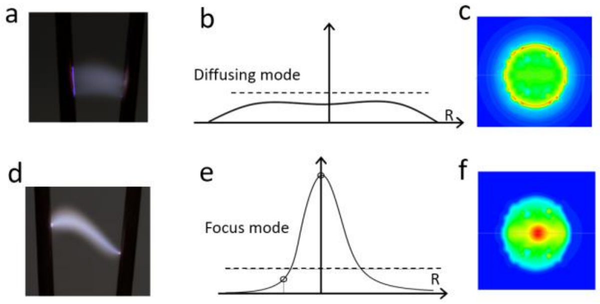

Figure 1. The NDR featured sheath layer and its effect on current density re-distribution. (a) Diffusing mode of arc attachment. (b) and (c) represent the arc density profile for diffusing mode. (d) Focus mode of arc attachments. (e and f) represent the current density distribution over the arc root. (The contours are obtained by simulation).

Beyond the existing modelling method for arc dynamics[10, 38, 43], the sheath has been implemented as a nonlinear layer. The plasma is assumed to be in ionization equilibrium and its composition is computed by the Saha equation . The transport properties of the plasma mixture can be calculated by Boltzmann’s integral-differential equation using the Chapman-Enskog method [45, 46].

The explicit expression for the voltage drops as a function of current density is assume as the curve as shown in **Figure 2**. This relation ensures the voltage drop changes gradually with respect to the current density. The mathematical expression of voltage drop function is difficult to decide and expected to depart from the curve given for an illustrative purpose, but the major feature of this curve should be similar.

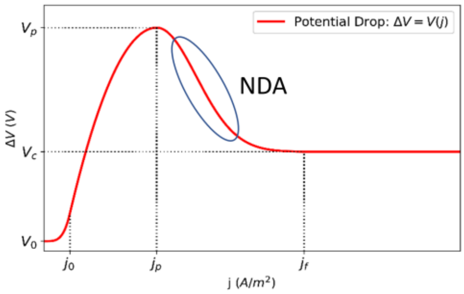

Figure 2. The relation between the voltage drops across the sheath layer. This is an approximation that there is a segment features negative differential resistance (negative resistance).

Under low current discharge condition (like grow discharge), the current density distribution at the arc attachments is in a diffuse mode as shown in Figure 1(a). The temporal evolution of arc attachment is subject to self-increasing impedance. For example, the increase of local current density will cause the decrease of conductance which prevents the local current density from increasing, and vice versa. Once the maximum current density exceeds the critical current density, the arc attachment state will be unstable. For example, under controlled discharge current, if the maximum current density is at attachment center, the conductivity at the center will also be largest and will continue to increase, which will make the attachments constricts further. Thus, the spot becomes more and more conspicuous as shown in Figure 3.

As an analogy, the sheath layer, plasma bulk and electrode are connected in series, which can be regarded as a negative resistor connecting a normal resister as illustrated in Figure 1. Because of negative resistance, there will be a bistable region for the circuit current in each branch. The arc attachments can be regarded as a parallel circuit with infinite branches, and thus the bistable current in each branch will together contribute to multiple-stable modes of current density distribution as illustrated in Figure 3. For example, if the branch in the central area subject to a positive perturbation, then the current through the center branch will increase dramatically, which will account for a large potion for the total current. As a consequence, it becomes to the focus mode. This arc root model provides a unique tool to understand the negative resistance effect on the behavior of arc attachments.

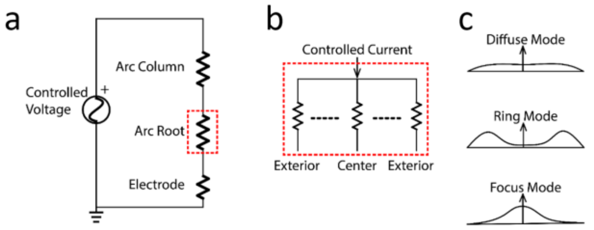

Figure 3. The negative resistance featured sheath layer and its effect on current density re-distribution. (a) The analogy of arc attachments by a circuit system. (b) Each branch has a bistable region for circuit current. (c) The possible modes of current density distribution and pattern formation at arc attachments: diffuse mode, ring mode and focus mode.

Apart from the interfacial negative resistance, it has been reported that the arc attachment modes are affected by factors like the thermal state of electrodes, the amplitude of discharge current and electrical conductivity of electrodes[25, 47, 48], therefore the spatial-temporal evolution of pattern formation at arc attachments needs further study.

3. Conclusion

In this paper, we discussed the instability of arc attachment and detachment on the solid counterparts such that the arc roots can be in either diffusing mode or constricted mode. The increase of current density into the negative resistance region will possibly cause the arc jumping and develop a new arc attachment. On the contrary, any decrease of current density at arc root will be a propagating decrease until the extinction of the arc root. The reason why arc roots jump is that in the neighborhood of arc attachment is that the location with higher current density has a higher growth rate, as a result of which the arc root will constrict to a more conspicuous one. This constriction immobilizes the arc attachment until a newly formed arc root replaces it. Multiple arc roots can coexist during this replacement process and follow a dynamic evolvement. In general, this finding could help to understand and the arc-electrode interaction and thus to control it, which can be applied in a broad range of applications, such as improving the design of circuit breakers, controlling plasma etching, and promoting plasma propulsion.

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