

Effect of Electrode Material to Current-Voltage Characteristics of a Gerdien Condenser

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Effects due to kind of materials used for the collector electrode of a Gerdien condenser upon the current-voltage (I - V) characteristics were investigated. Aluminum, copper and nickel electrodes were initially polished and cleaned and the I - V characteristics were recorded with 15-minutes interval under exposure to ambient air. Results showed that the zero-crossing voltage in the I - V curve shifted toward negative electrical potential, while the saturation current decreased in accordance with the passage of time. The electrode surfaces showed clear change in the color after operation. Ion mobilities and ion species concentrations were determined from the measured I - V characteristics and they indicate sizable difference by the electrode aging effect. The aluminum electrode showed stable positive and negative saturation currents within 180 minutes, while the saturation current decreased down to 50% of the initial value.

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1. Introduction

The Gerdien condenser technique has been widely used in atmospheric science to identify the ion mobility, density and electric conductivity from the troposphere to mesosphere region [1–5]. Besides its traditional usage, the technique can also give information on atmospheric pressure plasma, and we have reported results of a miniaturized Gerdien condenser for laboratory-produced atmospheric pressure plasmas [6]. The miniaturized condenser was capable of determining ion mobility with the density of atmospheric pressure plasmas from the obtained current-voltage (I - V) characteristics. We also showed that the increase in fan flow rate affects the air flow field surrounding the plasma resulting to an apparent decrease in measured total ion density. One should be cautious in data analysis based on an I - V characteristic of the condenser, as it is affected by operation conditions other than the gas flow rate.

One factor that should possibly affect the measured I - V characteristics is the electrode material. Aging has been a normal phenomenon for electrode material which causes discrepancies on its performance. Baglin reported that the technical materials utilized for particle accelerators yields different results due to the effect of oxide layer and of the adsorbed water on the surface [7]. Work function of metal surface can change depending upon adsorbate, while the change alters potential difference between electrodes of the condenser. Thus, the effects of the individual electrode component are currently being investigated in order to optimize the capability of Gerdien condenser for characterization of atmospheric pressure plasmas.

The most common material used to make Gerdien condenser devices is brass [2, 3] following the successful use of the material for ion mobility measurement. However, for utilization with radiosondes, the Gerdien condenser device has to be made of durable and lighter materials such as aluminum. Aplin briefly discussed about the effect of tube material but only on chemical reactivity [4]. She preferred stainless steel to aluminum as a more reliable electrode material. Wahlin reported that the electrode material causes an offset on the I - V characteristics which is due to the contact potential difference of the material [8]. Meanwhile, Harrison suggests that the change in temperature affects the variation in voltage offset [9]. Some researchers suggested voltage offset values to counteract the current offset depending on the material. For example, Wahlin suggested that copper should be biased at -0.45 V while aluminum at -1 V bias. Hatakayama [10] applied an offset of -140 mV for aluminum, however they did not explain how the quantity was obtained.

Another solution was to plate the electrode with a more stable material. Widdel applied nickel plating to aluminum after they have observed that the shift in the I - V characteristics may be caused by the insulating oxide layer which is always present on untreated aluminum surface [5]. Meanwhile, Das utilized a brass electrode electroplated with nickel for a polished corrosion free surface [11]. However, there is no report if the observed offset on the I - V characteristics diminished after plating the electrode. Although some researchers suggested different solutions to counteract the current offset, the effect of the electrode material has not been comprehensively investigated.

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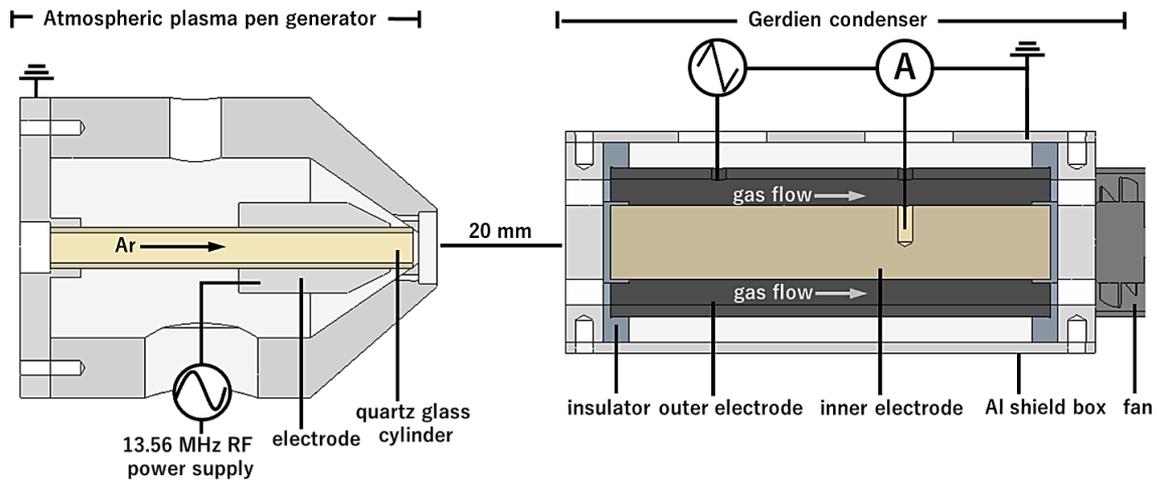


Fig. 1 Schematic diagram of the experimental setup utilizing the Gerdien condenser device [right] at 20 mm distance apart from the atmospheric plasma pen generator [left].

It is important to analyze the effect of the electrode material to the I - V characteristics for more reliable treatment of data to deduce plasma parameters by using a Gerdien condenser.

2. Experimental Methods

A 6.0 cm long Gerdien condenser with 0.85 cm and 0.5 cm outer and inner radius, respectively was designed and fabricated for characterizing laboratory-produced atmospheric pressure plasma. The entire condenser as shown in Fig. 1 is mounted in an electrically grounded aluminum rectangular shield box. A 2.5 cm by 2.5 cm fan with gas flow rate of $750 \text{ cm}^3/\text{s}$ is attached at the end of the condenser to create a flow field and drag ions into the region of ion collector electrode.

2.1 Plasma generator

Figure 1 also shows the schematic diagram of an atmospheric pressure plasma (APP) generator operated with 13.56 MHz AC power source. The RF power is supplied to a 2.5 cm long aluminum electrode attached on a 0.7 cm diameter 5.7 cm long quartz glass cylinder through which Ar gas flows to maintain a discharge. A flow controller regulates Ar supply to the generator at 3.0 liter per minute, and the APP were ignited and sustained at 30 W forward input power. Typical reflected power to the source did not exceed 1.5 W.

2.2 Gerdien condenser operation

Three pairs of inner and outer electrodes, specifically made of aluminum, copper and nickel, were initially polished using 600 and 1200 abrasive papers, and then rinsed with ethanol. The assembled Gerdien condenser was positioned 2.0 cm away from the plasma exit nozzle. A voltage sweep from -20 V to 20 V was applied to the outer electrode while the current was measured at the inner elec-

trode. An I - V characteristic was recorded 15 minutes after polishing and assembling the Gerdien condenser of each electrode material. Traces were subsequently recorded after every 30 minutes over the period of 3 hours. Images of the inner electrodes before and after the operation were taken using an optical digital microscope (*Shodensha* TG500PC2 5.0 megapixel USB microscope).

3. Experimental Results

3.1 Current-voltage characteristics

Figure 2(a) shows the raw data of the applied voltage to the outer electrode with sweep duration of 20 seconds and the typical current behavior measured by the inner electrode of the Gerdien condenser as a function of time. Substantial amount of the displacement current was observed when the voltage sweep rate of the bias electrode exceeded about 8 V/s . After subtracting the displacement current for sweep durations of 0.1 and 5 seconds, the measured I - V characteristics were nearly identical as shown in Fig. 2(b). Hence, the voltage sweep time duration was set to 20 seconds in this study to eliminate contribution from displacement current onto the measured I - V characteristics. Noise arising from atmospheric pressure discharge was filtered out through a low pass filter with end pass band of 2 Hz then the I - V characteristics are smoothened. It is important to note that there is asymmetry between I - V characteristics of positive and negative ions for higher voltages as shown by the inset in Fig. 2(b). The difference in the slope region and on the saturation current is due to the difference in the ion species collected by the Gerdien condenser depending upon the polarity of the applied voltage. Further discussion on ion mobility and density is included in Sec. 4.3.

Shown in Fig. 3 are the I - V characteristics after smoothening. They are acquired using the fresh electrodes and 180 minutes after exposure to ambient air. Each ma-

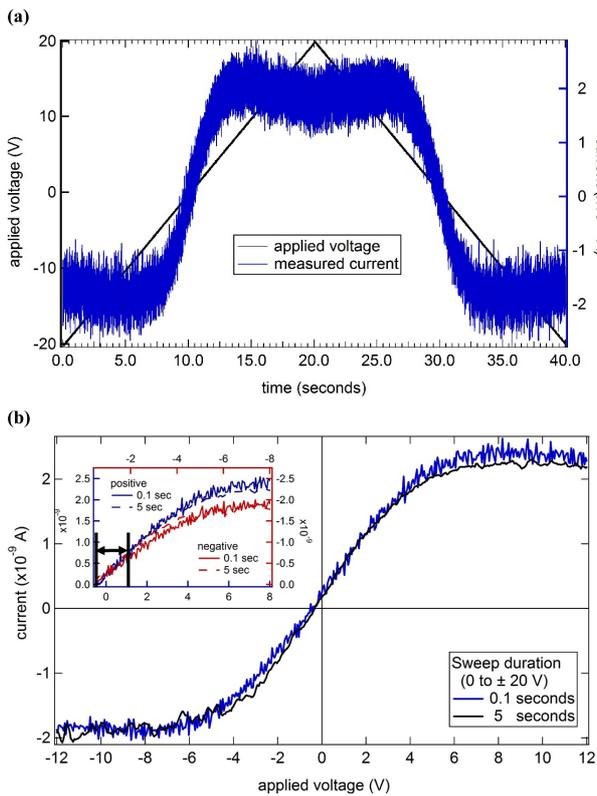


Fig. 2 (a) Raw data of bias voltage with 20 seconds sweep duration and measured current as a function of time and (b) I - V characteristics for bias voltage sweep duration of 0.1 seconds and 5 seconds after subtracting the effect of displacement current.

material exhibits a unique I - V characteristics behavior as depicted in Fig. 3. The acquired ion current indeed showed dependence upon the change in the electrode surface condition hence different results were obtained when the material was varied. Initially when the electrode surfaces were freshly cleaned, all the materials exhibited similar saturation current, I_{sat} when the applied voltage was positive to let the collector electrode to detect positive ions. However, when the bias voltage was negative, the obtained I_{sat} diverged significantly depending upon the electrode material. The largest positive I_{sat} was measured for copper electrode while the lowest current was measured for nickel. After exposing the electrodes to ambient air for about 180 minutes, I_{sat} dropped for both positive and negative ion measurement. However, the amount of the current drop was larger for negative ion collection, where copper electrode recorded a decrease by 8×10^{-10} A. For positive ion collection, the largest drop in I_{sat} is 4×10^{-10} A which was observed for aluminum electrode. The obtained values of I_{sat} are listed in Table 1. It was surprising to observe, that negative saturation currents were completely different from the fresh electrode surface condition, while the positive saturation currents for three electrode materials were similar for fresh electrodes.

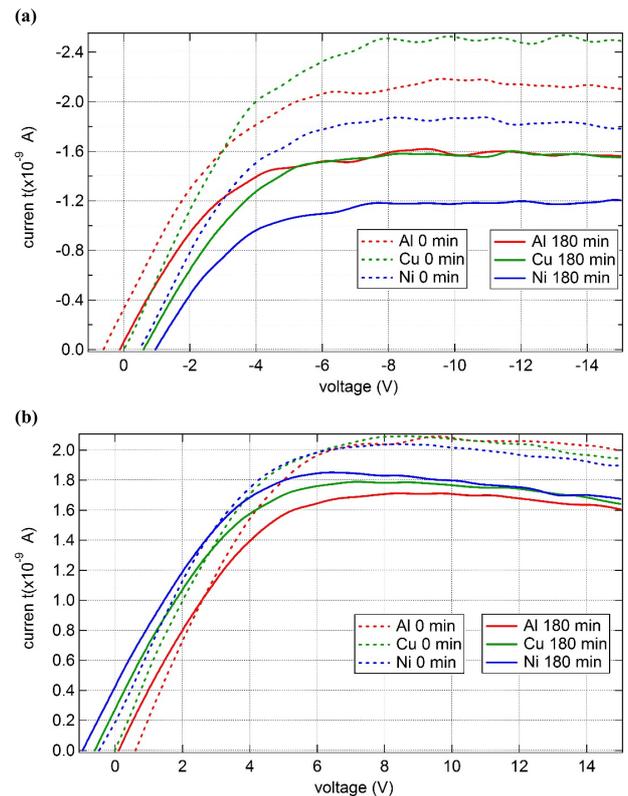


Fig. 3 Current-voltage characteristics obtained for measurement of (a) negative and (b) positive ions using fresh electrodes and 3 hours after exposure to ambient air.

Table 1 Saturation current measured from the I - V characteristics.

Material	$I_{sat} [-1 \times 10^{-9} \text{ A}]$ (negative bias)		$I_{sat} [1 \times 10^{-9} \text{ A}]$ (positive bias)	
	0 min	180 min	0 min	180 min
Al	2.2	1.6	2.1	1.7
Cu	2.4	1.6	2.1	1.9
Ni	1.7	1.2	2.1	2.0

3.2 Electrode potential

Another distinct difference observed in the I - V characteristics was the shift in the electrode potential, ΔV , defined as the bias voltage when the measured current is equal to zero. The electrode potential varies depending on the material, resulting in different shifts in I - V characteristics on the abscissa. Clear differences between fresh and atmosphere exposed electrodes are easily seen in Fig. 4, which shows the entire I - V characteristics during a voltage sweep for nickel electrode. First, the drop in saturation current for both negative and positive measurement is evident. Secondly, the I - V characteristics shift according to the change in electrode potential which is observed to be an effect of long exposure to ambient air.

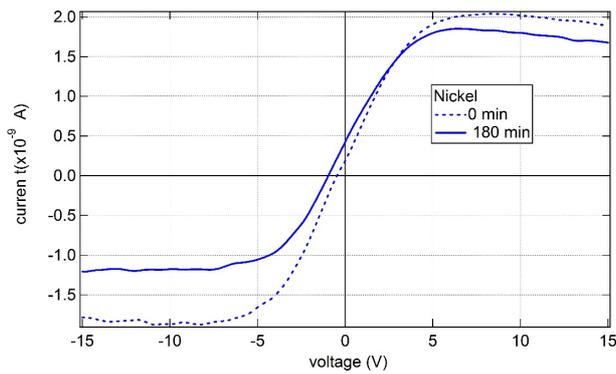


Fig. 4 *I-V* characteristics of nickel from -15 to 15 V sweep.

4. Discussion

4.1 Change in surface condition

The decrease in measured saturation currents and shift in voltage which are exhibited by all materials suggest that there is accumulation of adsorbates on the electrode surface affecting the current collection by the electrode, and surface potential barrier. Shown in Fig. 5 are the images of the electrodes before and after exposure to ambient air. Although copper demonstrates the most noticeable surface change, aluminum and nickel also displayed a varied surface condition visible to the naked eyes. It is presumed that the adsorbates that have developed on the electrodes are oxide layers that occurs naturally on an exposed metal surface but with patterns relevant to ion collection.

Shown in Fig. 6 is the graph of electrode potentials of all materials as function of time. For all material, the electrode potentials approached to values more negative than the initial values. They tend to saturate after around 90 to 120 minutes. Only aluminum yielded a positive offset on *I-V* characteristics for both initial and final trace. Copper and nickel both have negative electrode potentials initially, but nickel exhibited the most negative value.

Surface properties like work function should mainly determine the electrode potential. Wahlin, for example, discussed that the effect of contact potential is eliminated since Gerdien condenser comprises of electrodes of the same material. However, since the surface conditions of inner and outer electrodes become different due to exposure of ion current at different current density, we may observe asymmetric saturation current. The asymmetry also enlarges as the exposure to APP, which is consistent with the progress of surface modification by charged particles/oxidation. On the other hand, there can be also a contribution due to space charge inside of the condenser. The electrical contact potential difference between the electrodes is also relevant to the oxidation chemical potential of the material. Since aluminum has the highest tendency to oxidize, it can develop the most passivated surface compared with other two materials.

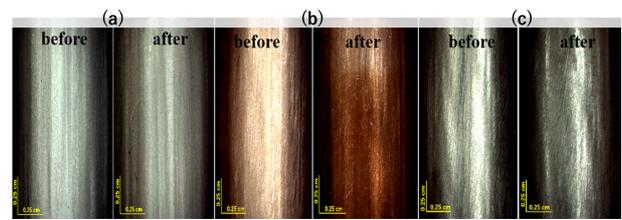


Fig. 5 Images of (a) aluminum, (b) copper, and (c) nickel electrodes before and after exposure to ambient air.

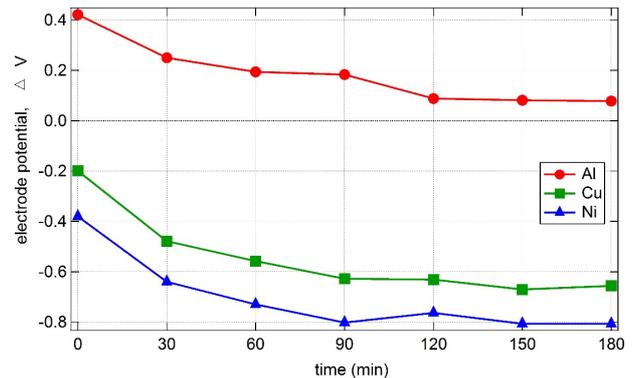


Fig. 6 Change in electrode potentials of all materials utilized over time.

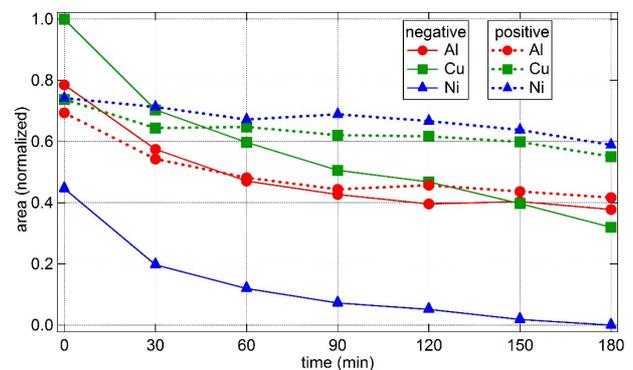


Fig. 7 Area under the *I-V* characteristics from the measured electrode potential to ± 20 V.

4.2 Stability

Stability in *I-V* characteristics is necessary for reliable analysis; if we know how the aging of the collector electrode develops, we do not have to polish the electrode every time but utilize “saturated” electrode. To examine the stability of each material over time, the change in the area under the *I-V* characteristics is calculated and plotted as shown in Fig. 7. The area is obtained by integrating the current from the obtained ΔV to ± 20 V. From this figure, an exponential curve is fitted and the time constant for each material are derived as listed in Table 2.

The measurements obtained using aluminum electrode seems to achieve saturation for both positive and neg-

Table 2 Time constant calculated from exponential curves fitted in Fig. 7.

Material	Positive bias	Negative bias
Al	36.6	40.6
Cu	99.6	70.4
Ni	----	40.7

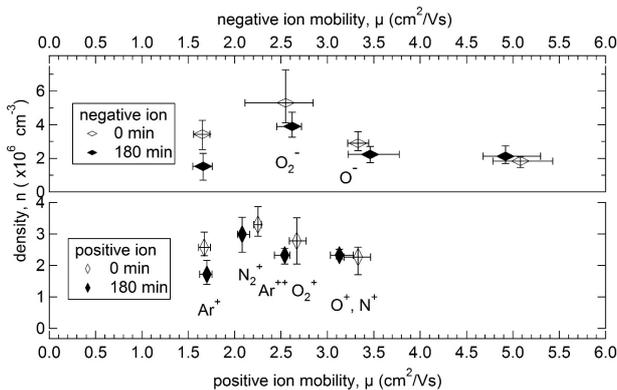


Fig. 8 Ion mobility derived before and after 180 min exposure to ambient air by applying negative [top] and positive [bottom] bias.

ative ion measurements with reasonably fast time constant. On the other hand, the I - V characteristics obtained using copper continued to decrease for both positive and negative ion collection. Nickel yielded most stable positive ion measurements but the current measured during negative ion collection declined similar to aluminum.

4.3 Ion mobility and ion density

Figure 8 shows the detected positive and negative ion mobilities and their corresponding density. The individual ion densities are evaluated similar to the method discussed by Burt [12]. The uncertainties shown in the figure are from the variation of mobility and density values calculated from the three materials utilized. All the materials yielded similar negative and positive ion mobilities which are identified to be those of Ar^+ , Ar^{++} , N^+ , N_2^+ , O^+ , O^- , O_2^+ and O_2^- [13, 14]. Hence, the detected ion species are not dependent on the electrode material utilized. The negative ion mobility around $5.0 \text{ cm}^2/\text{Vs}$ may be due to the electrons, while $1.5 \text{ cm}^2/\text{Vs}$ may be due to negative ion cluster which is yet to be identified. To observe the effect of change in surface condition, the ion mobility is also derived after long exposure to ambient air.

The ion mobilities are observed to shift possibly due to the shift in electrode potential. Hence, in order to obtain an ion mobility spectrum with the effect of electrode potential eliminated, the I - V characteristics can be shifted accordingly.

Table 3 Total ion densities of positive and negative ions detected by the Gerdien condenser.

Material	Negative ion density [$1 \times 10^7 \text{ cm}^{-3}$]		Positive ion density [$1 \times 10^7 \text{ cm}^{-3}$]	
	0 min	180 min	0 min	180 min
Al	1.8	1.33	1.75	1.42
Cu	1.99	1.33	1.75	1.58
Ni	1.42	1.0	1.75	1.66

Listed in Table 3 are the calculated total positive and negative ion densities for all materials measured before and after exposure to ambient air. The total ion densities are calculated using the same method as Ref. [6]. Parallel to I_{sat} behavior in Sec. 3.1, the same positive ion density is attained only when fresh electrodes are used. The highest negative ion density is attained when fresh copper electrode is utilized. After the 3-hour period, the measured densities for both positive and negative ions were observed to decrease. Nickel tends to favor positive ion collection resulting to the highest positive ion density measured. Correspondingly, nickel yielded the lowest negative ion density measured even when fresh electrodes are used.

5. Conclusion

The effect of electrode material to the Gerdien condenser I - V characteristics are studied to investigate suitable material for atmospheric pressure plasma diagnostics. The I - V characteristics yielded different electrode potential dependent on the material and its surface condition. There were observed shifts in the ion mobility spectra, but the ion species detected by the condenser remain nearly unaltered if the electrode potential shift is considered. The calculated ion density differs depending on the material, but the deviations were less than an order of magnitude difference.

Acknowledgments

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