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Current noise up to GHz band generated by slowly breaking silver-compound contacts with external dc magnetic field

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Abstract. Since electromagnetic (EM) noise resulting from an arc discharge disturbs other electric devices, parameters on electromagnetic compatibility, as well as lifetime and reliability, are important properties for electrical contacts. To clarify the characteristics and the mechanism of the generation of the EM noise, the current noise up to GHz band frequency generated by slowly breaking contacts with external direct current (dc) magnetic field, up to 40 mT, was investigated experimentally using Ag and $AgSnO_2$ material. To reveal the characteristics as pure clean surface contact operation, the arc only at the operation of the first contact break was measured. Firstly, the effect of the external dc magnetic field on the duration and voltage fluctuation of the breaking arc of $AgSnO_2$ material, which has relatively longer arc duration, was quantified. The experimental results on $AgSnO_2$ material newly revealed that although applying external dc magnetic field is effective in reduction of duration of gaseous phase in arc discharge, higher variation of contact voltage in the gaseous phase which results in high frequency noise is caused. Secondly, the effect of the external dc magnetic field on the breaking arc of Ag was measured. It was found that larger current noise arises, when the contact voltage is rapidly varied at the arc discharge. There are two kinds of rapid changes, which cause high-frequency EMC problem, in the voltage waveform. One is at extinction of arc discharge. Other kind is short-duration arc (short-arc) before the ignition of the continuous metallic arc. Especially, we focused on the characteristics of the short-arc at the initial of the opening of the contact for clarifying the high frequency EMC problem. It was demonstrated that the spectrum of current noise in the case of "$B = 30$ mT" is smaller than that in the case of "$B = 0$ mT". In addition, duration and fluctuation of short-arc is suppressed by the dc magnetic field. These results are basic and useful finding to know not only the noise generation in the contact-breaking phenomena but also the material dependency for EMC problems.

PACS. 52.80.-s Electric discharges – 52.70.Gw Radio-frequency and microwave measurements – 52.25.Os Emission, absorption, and scattering of electromagnetic radiation

1 Introduction

The electrical contact devices made by metallic materials are still important to make or break circuit current and/or voltage. It is known that the arc discharge causes not only degradation of the device, such as welding or erosion of contacts, but also the cause of electromagnetic (EM) noise, as electrical environmental problem over GHz frequency bandwidth. Since the EM noises radiated from the switching and an arc discharging disturb electronic devices, electromagnetic compatibility (EMC) issue should be an important point of view to evaluate the quality of electrical contacts [1]. EMC design for electrical contacts is still difficult because of our incomplete knowledge of the fundamental noise generation mechanism that produces EM radiation.

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So far, arc phenomena have been discussed from various viewpoints in all its aspects [1–4]. The authors have published literatures on current and radiation noises from 1 MHz to 3 GHz of Ag, Cd and Sn compounds at breaking contact [5–7].

It is well known that the external magnetic field is applied to electrical contact to make arc discharge shorter. Lorentz force is considered one of cause to make change of the phenomena [4,8]. The EMC view point should be taken into account to design the contact. But, still we need more knowledge of the phenomena and the fundamental noise generation mechanism.

In this paper, the measurement and some considerations on current noise and waveform up to GHz frequency band generated by very slowly breaking contact with external dc magnetic field are reported. This paper newly attempts to clarify the mechanism of the generation of high frequency EM noise generated by breaking contact at

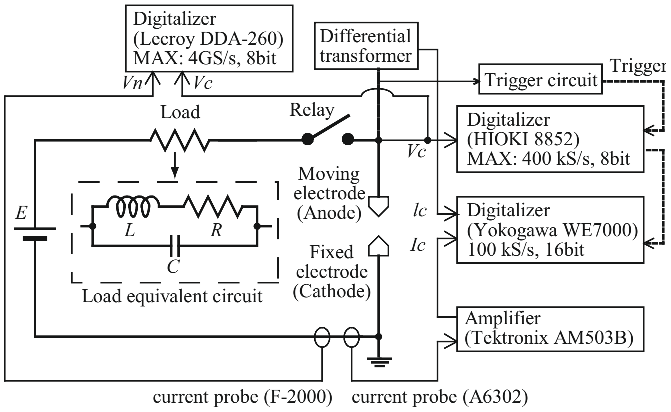


Fig. 1. Experimental set up for opening waveforms measurement.

transition from bridge to arc, and the effect of the external dc magnetic field on the EM noise as well as arcing phenomena. The bridge generation and arc-phenomena are influenced by thermal condition as well as electrical condition. The very slowly opening velocity of the moving electrode was selected so that it satisfies quasi-thermal equilibrium condition. The arc only at the operation of the first contact break is remarked. It is because the first operation is expected to reveal the characteristics as pure clean surface contact breaking operation. The materials picked up in this paper are silver and silver-tin alloy, because we expect to make clear the differences of material and arc duration.

2 Experimental method

2.1 Experimental set up

The set up for the measurement, shown in Figure 1, is developed in order to take data for the correspondence of noise generation to contact breaking phenomena. The contact voltage V_c, the contact current I_c, the displacement of moving contact l_c, and current noise as EM noise picked up by high frequency current probe V_n are measured simultaneously. Voltage V_c measured by a voltage probe (up to 500 MHz) and current noise measured by a current probe (Fischer F-2000, up to 3 GHz) are digitalized by an oscilloscope (Lecroy DDA-260, 4GS/s, 8bit). I_c was monitored by a clamp type current probe (Tektronix A6302+AM503B). l_c was picked up with differential transformer (Elgo Japan EDT-1.5). The open-voltage E was selected as 36 V to take into account a future supply power of equipments for an automobile. The close-current I, 4.7 A, was determined by rated range of a load resistor. Although the load resistor was expected as non-inductive resistance of 8 Ω, the cables and the holders have inductance L and capacitance C. Then, an equivalent circuit of the resistor was measured with network analyzer (Hewlett Packard 4195A), shown in Figure 1 and Table 1. The movement of breaking the contact was performed by using synchronous motor and swash plate cam [9]. The beginning of the measurement was determined by the detection of the electrical touch between the swash plate cam and cam follower [10]. The opening velocity of the moving electrode was about 70 μm/s and it was determined so that it satisfies quasi-thermal equilibrium condition. The fixed and moving electrodes were the anode and cathode in the experiment, respectively.

Table 1. Test conditions.

Open voltage E	36 V (battery of 12 V (nominal) × 3)
Load	$R = 8.01\ \Omega$ ($L = 279$ nH, $C = 17.8$ pF)
Close current I	4.7 A
Material	$Ag_{90.7}SnO_2$, Ag
Electrode shapes	2.5 mm ϕ flat type rivet electrode
Opening velocity	about 70 μm/s
Atmosphere	Temperature 19−29 ℃ Humidity 32−41%
Magnetic field	0, 10, 20, 30, 40 mT

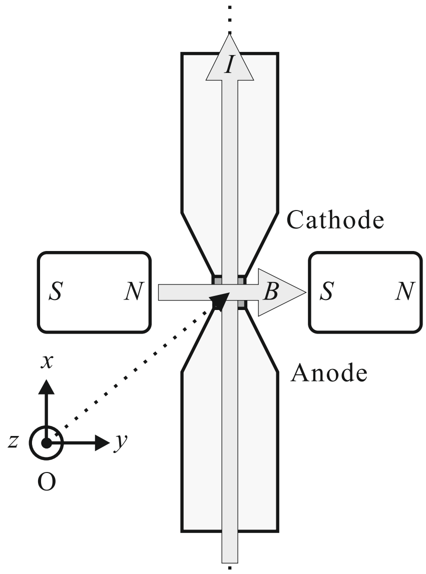


Fig. 2. Illustration of the magnetic field and contacts.

Magnet of $Nd_2Fe_{14}B$ is used to apply dc external magnetic field. As it is a strong alloy magnet, magnetic field strength at the contacts point can be changed simply by changing distance from pole of magnet to electrodes. Figure 2 illustrates the positioning of the magnet and contacts and Figure 3 shows a typical magnetic field distribution near the magnets. The magnetic field distribution is sufficient to cover the arc length, which is a few mm order.

2.2 Materials

Ag and $Ag_{90.7}SnO_2$ are chosen as the contact test materials. After the ultrasonic cleansing in alcohol and distilled water and the drying are done, the electrode is mounted to the holder for the measurement. The data of the first time operation of the opening movement is recorded as

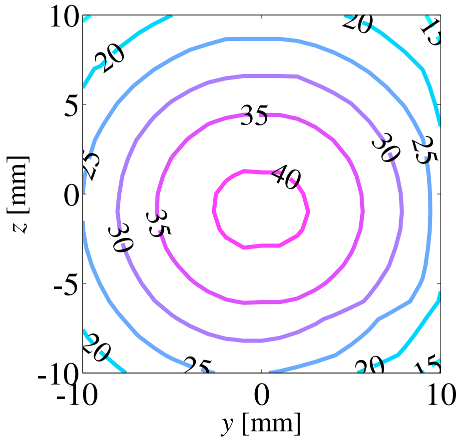


Fig. 3. (Color online) A typical magnetic distribution in y–z plane at $x = 0$.

one trial. Several trials are performed by the replace of electrodes to make results in this paper. Table 1 is the summarized test conditions.

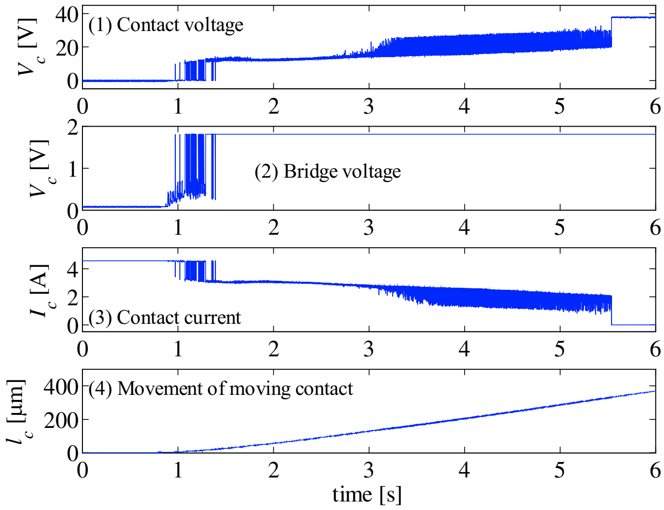
3 Experimental results and discussion

3.1 $AgSnO_2$ contact

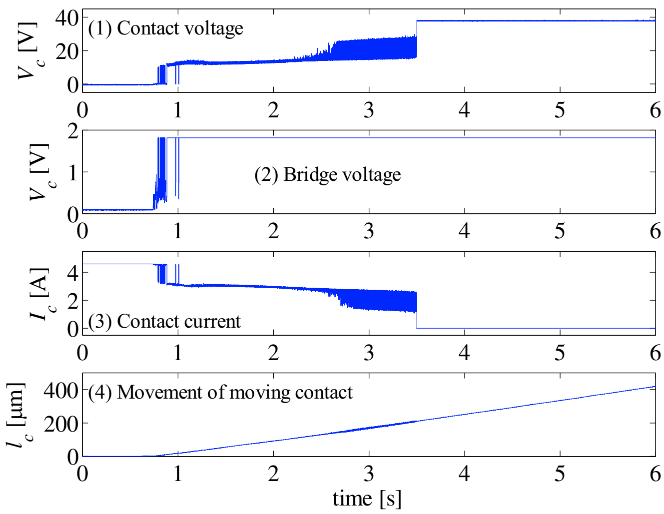
Figure 4 shows typical waveform of $AgSnO_2$ without magnetic field, in which (1) is contact voltage sampled by 200 kHz, (2) the scale-up of the longitudinal in (1), (3) contact current sampled by 100 kHz, and (4) displacement of moving contact. Figure 4b shows a typical waveform with magnetic field of $B = 30$ mT. The arc discharge in the "without external magnetic field" case is extinguished when displacement of the moving contact is approximately $l_c = 380$ μm. This phenomenon is in good agreement with the extinction-gap of contacts L_c estimated by the V-I characteristic in literature [2]. On the other hand, the arc discharge in the "$B = 30$ mT" case is extinguished when $l_c = 200$ μm. This result means that arc duration is reduced to one-half by applying the external magnetic field.

In order to understand the details of effect of external magnetic field on the breaking arc, the relationship between gap length, at which arc phase is changed, and external magnetic field strength is quantified and discussed. The relationship is shown in Figure 5, where the l_m is gap length when arc reached metallic phase, the l_g is gap length when arc is change from metallic phase to gaseous phase (contact voltage reaches 22 V [11]), and the l_e is extinction length. The effect of the external dc magnetic field is mainly observed on the shortening of arc duration. As the external magnetic field increases, l_e becomes shorter.

Figures 6a and 6b show picked up fluctuation waveforms without and with magnetic field, respectively. The samplings were performed by 200 kHz. Arc phenomena are distinguished by three arcing phases as bridge, metallic and gaseous phases. For the waveforms in the left hand side in the figure, 0 V for V_s indicates the voltage above



(a) $B = 0$ mT case



(b) $B = 30$ mT case

Fig. 4. (Color online) Typical measured results for the $AgSnO_2$ material case.

baseline voltage which may be minimum arc voltage. The right hand sides of the figures are histograms of the voltage fluctuation waveform. We cannot see remarkable difference of the bridge and metallic phase between with and without magnetic field. On the other hand, peak voltage in the histogram for the gaseous phase, magnetic field may make slightly higher peak voltage, higher than 10 V.

So, voltage fluctuation waveform near extinction in the "$B = 30$ mT" case is focused as EM noise source. Figure 7 shows the waveform measured by the 2 GHz oscilloscope. Fluctuation is observed near GHz band frequency, as shown in (c) by the FFT analysis. The waveform in Figure 7a has histogram as shown in Figure 8. It seems

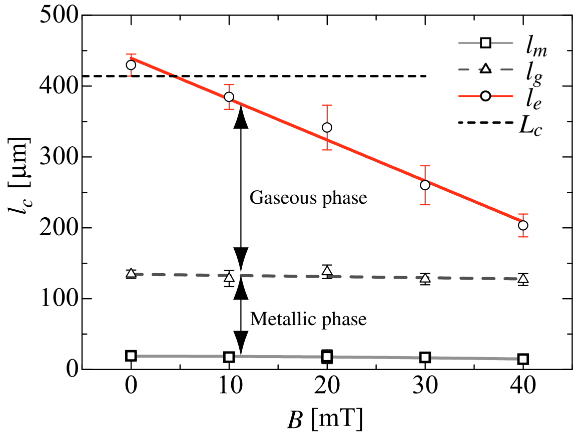
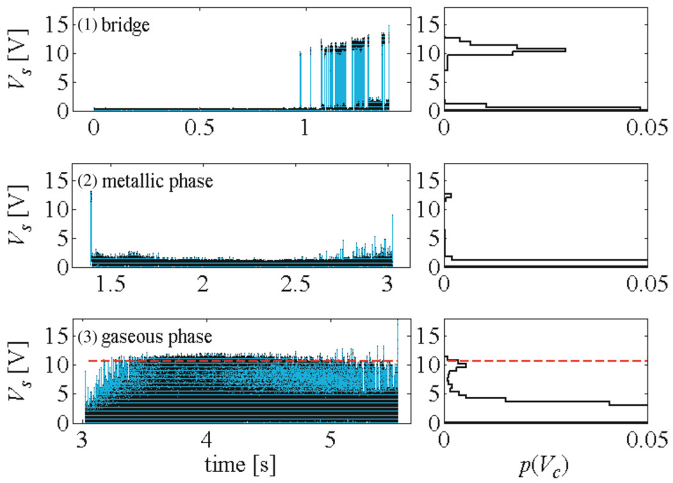
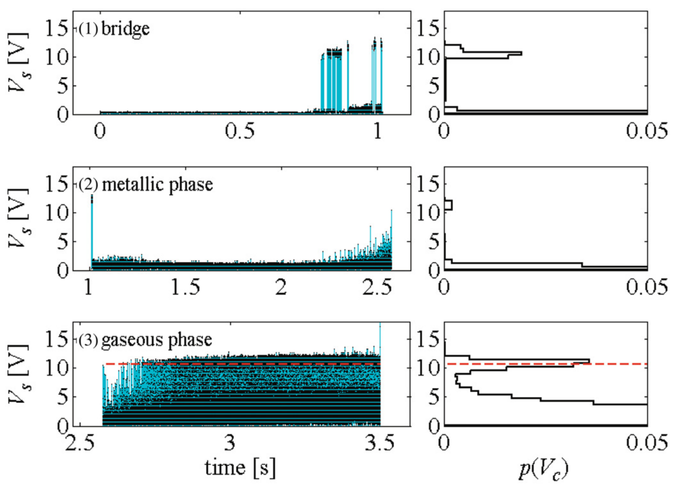


Fig. 5. (Color online) The relationship between gap length and external magnetic field.



(a) $B = 0$ mT case



(b) $B = 30$ mT case

Fig. 6. (Color online) Fluctuation of the arc voltage and amplitude histogram.

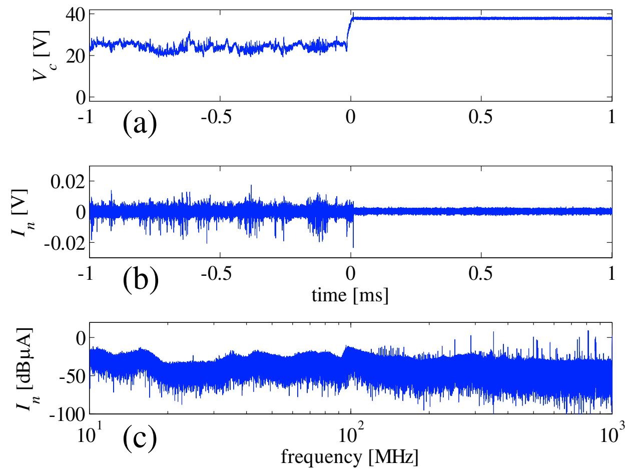


Fig. 7. (Color online) Fluctuation and spectrum of $AgSnO_2$ sampled by 2 GHz ($B = 30$ mT). (a) Arc voltage, (b) current noise, and (c) spectrum of the noise.

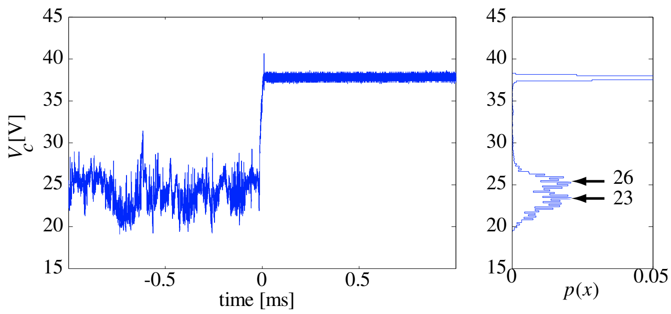


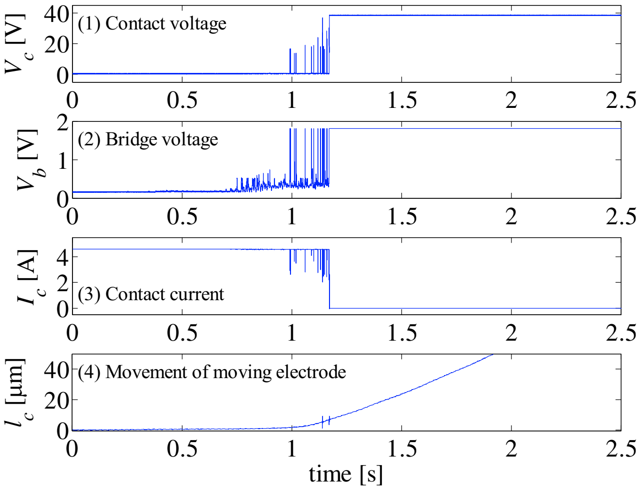
Fig. 8. (Color online) Histogram of the fluctuation of (a) the arc waveform of Figure 7.

that there are two peak voltages near 23 and 26 V. The mechanism of such peak of the fluctuation is still unclear.

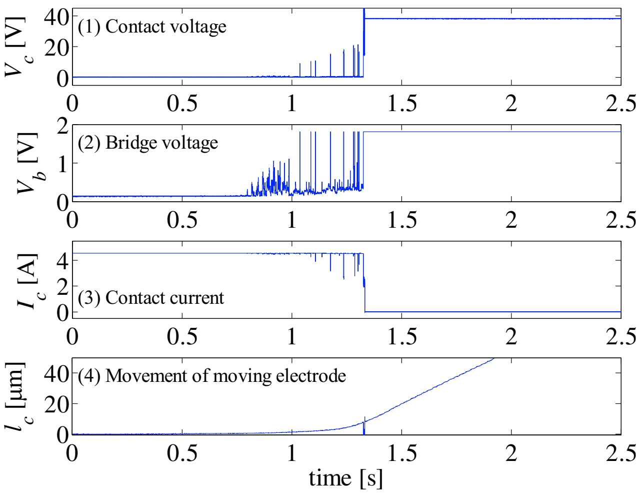
The duration of the arc for $AgSnO_2$ is longer than that of compared Ag contact as shown in the next section. It means the gaseous phase arc occurs at the first break of the $AgSnO_2$ contact. But we observed initial short arc at the beginning of the bridge to the metallic phase.

3.2 Ag contact

Figure 9 shows typical waveforms obtained for silver contact. (a) and (b) are for without and with $B = 30$ mT magnetic field cases, respectively. As the breaking speed of the contact is very slow, about 70 μm/s, comparably long bridge are observed. There are two types of rapid changes, which cause high-frequency EMC problem, in voltage waveform. One is at extinction of arc discharge. Another type is short-duration arc (short-arc) before the ignition of the continuous metallic arc discharge. At around 1 s in (1) and (2) of Figure 9, we cannot see the short-arc, but it is because of the slow sampling speed. When we use an oscilloscope with 2 GHz sampling, the short-arc was able to observed at the transient from a bridge to a stable arc. Ag has only arcing around milliseconds duration at the first operation of the contact break,

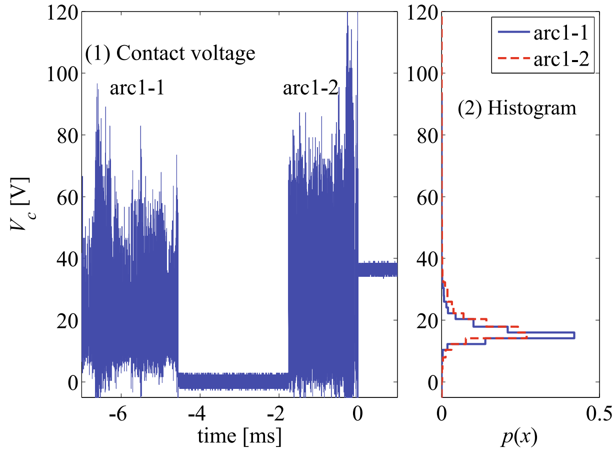


(a) $B = 0$ mT case

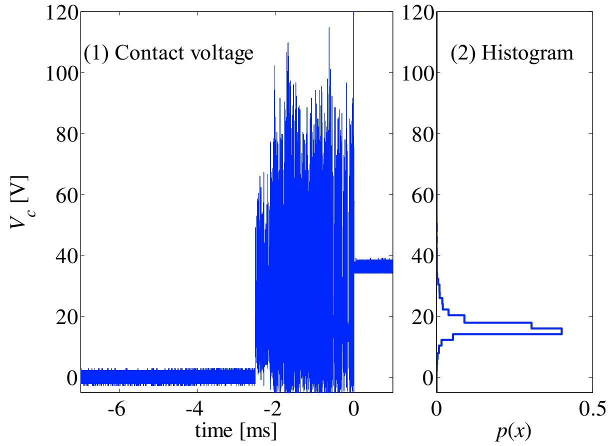


(b) $B = 30$ mT case

Fig. 9. (Color online) Typical measured results for the Ag material case.



(a) $B = 0$ mT case



(b) $B = 30$ mT case

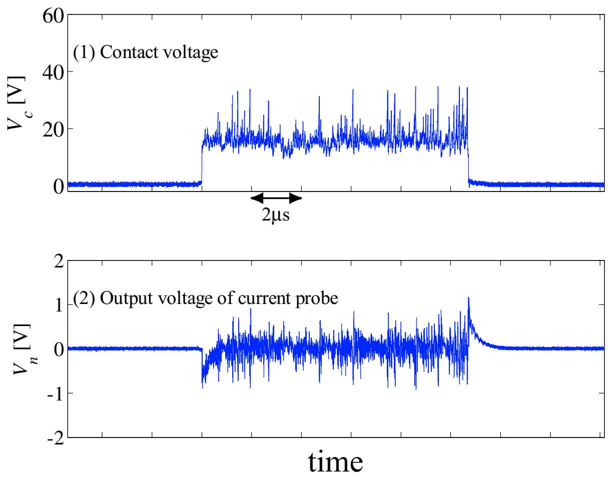
Fig. 10. (Color online) Waveform and histogram of the fluctuation of the arc waveform of Ag.

which is in the metallic phase. It was demonstrated that the arc duration becomes longer if we operate the same contact for several times [12].

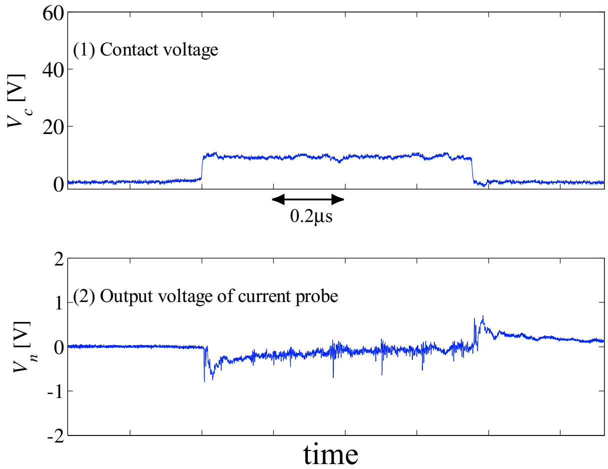
Figure 10 is typical arcing waveform at the extinction for silver contact. (a) and (b) are for the without and with 30 mT magnetic field cases, respectively. The histograms of the arcing waveform are shown at the right hand side in Figure 10. Though we cannot basically find out any differences of the histograms, high voltage arcing, higher than 120 V which is over quadruple larger than supply voltage, were observed.

We expected to reveal the characteristics of the very short-arc at the initial of the opening of the contact for clarifying the high frequency noise problem. Typical waveform of the short-arc at the initial part of the break sampled by 2 GHz is shown in Figure 11. Short-arc arises immediately after the temperature at a-spot reached boiling temperature. Then contact is closed (re-bridge). It is presumed that a melting-metal is formed to parallel to the arc-column and constructs re-bridge, when Coulomb force is larger than the surface tension at melting-metal surface [1]. Current fluctuations are occurred at just after the voltage fluctuation as shown in (2). The larger current fluctuations are at the ignition and extinction of short-arc. It is desired to compare the characteristics measured with magnetic field. By comparing the characteristics measured with magnetic field, it is demonstrated that applying the dc magnetic fields suppresses the duration and voltage fluctuation of short-arc.

To clarify the correspondence of noise generation to the contact-breaking phenomena in detail, the time-frequency domain characteristic of the current noise of short-arc is discussed. The time-frequency domain characteristic is

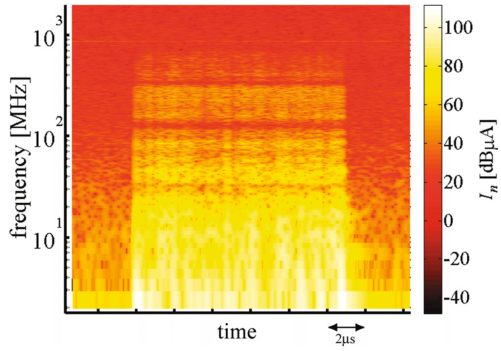


(a) $B = 0$ mT case

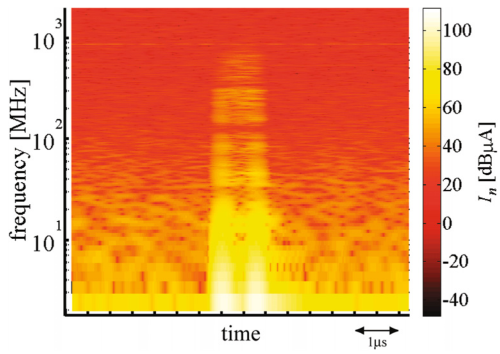


(b) $B = 30$ mT case

Fig. 11. (Color online) Short-time arc voltage and current noise of Ag.



(a) $B = 0$ mT case



(b) $B = 30$ mT case

Fig. 12. (Color online) Time-frequency domain characteristics of the current noise of short-time arc for Ag.

obtained from the current noise by using short-time FFT, and is shown in Figure 12, where the length of frame is 375 ns and the period of frame is 25 ns. At the "$B = 0$ mT" case, current noise arises over the whole short-arc. On the other hand, current noise at the "$B = 30$ mT" case has two peaks at the time immediately after the ignition and extinction of the short-arc. Figure 13 shows frequency spectrum of current noise, in which the spectrum is obtained from max value at each frequency in Figure 12. The current noise at the lower-frequency band (10 MHz) was the largest in the measured frequency range. Current noise decreases as the frequency increases. Current noise spectrum has antiresonance and resonance frequencies which correspond to the circuit admittance [7]. This decrease in current noise at higher frequencies may result from the decrease in the contact voltage at higher frequencies. Nevertheless, even if current noise at the GHz band is very small, it can cause a large radiation noise because of the high radiation efficiency. So slight current noise in μA order can not be disregarded. For effect of applying the dc magnetic field, current noise in the case of "$B = 30$ mT" is smaller than that in the case of "$B = 0$ mT". Suppression effectiveness of applying the 30 mT dc magnetic field is approximately 10 dB.

To discuss effect of magnetic field on current noise quantitatively from view points of the duration and the arc-voltage, effects of applying dc external magnetic field on arc-voltage and arc-duration are shown in Figure 14. The highest probability density voltage is defined as short-arc sustainable voltage (SASV). Results indicate that applying dc external magnetic field is effective in suppressing arc duration as well as SASV.

Figure 15 shows the relationship between SASV and duration of short-arc. It is revealed that as the SASV is higher, its duration becomes longer. This means larger SASV maintains longer arc duration.

Scatter diagram of the arc duration and noise intensity around resonance frequency of the current noise is depicted as in Figure 16. It is suggested that longer duration

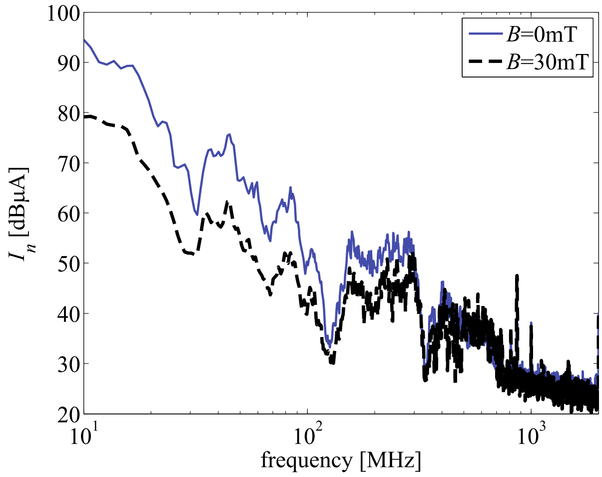


Fig. 13. (Color online) Frequency spectrum of current noise.

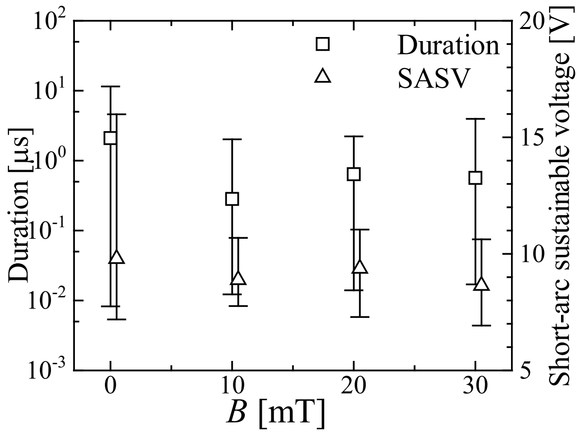


Fig. 14. Magnetic field strength vs. SASV and arc duration.

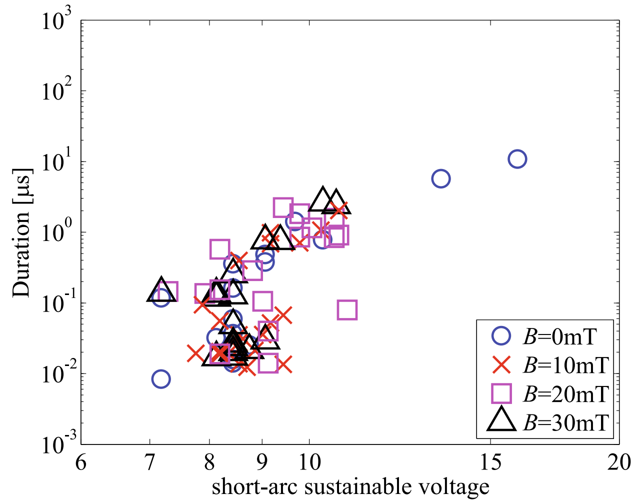


Fig. 15. (Color online) Short-arc sustainable voltage vs. arc duration.

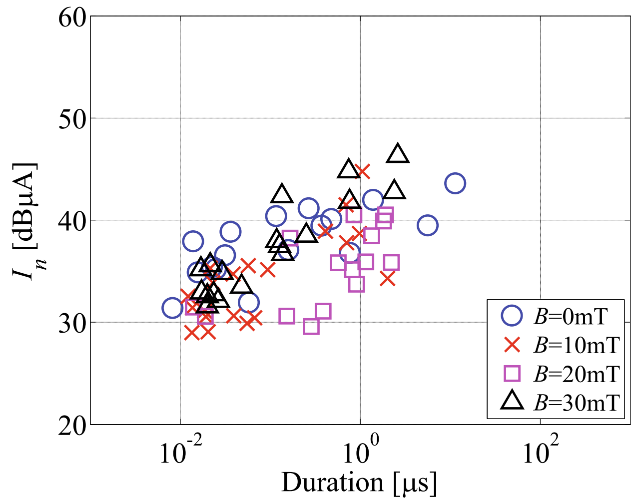


Fig. 16. (Color online) Arc duration vs. current noise at the bandwidth of 380–420 MHz resonance frequency.

of the arc makes larger current noise. As the duration increases, EM interference becomes more significant problem. So, SASV is can be considered as one of key parameters for evaluating and providing insight regarding the EMC design for contacts.

Consequently, as magnetic field influences on arc duration, the external magnetic field is effective in suppressing high-frequency current noise, at the initial short-arc.

4 Conclusions

Current noise up to GHz frequency band generated by very slowly breaking contact with external dc magnetic field was studied experimentally, to clarify the characteristics and the mechanism of the generation of the EM noise. To reveal the characteristics as pure clean surface contact operation, the arc of only first operation of the first contact break was measured. The materials chosen here are Ag and $AgSnO_2$, because we expect to make clear the differences of material and arc duration.

Firstly, the effect of the external dc magnetic field on the duration and voltage fluctuation of the breaking arc of $AgSnO_2$ material, which has relatively longer arc duration, was quantified. The experimental results on $AgSnO_2$ material newly revealed that although applying external dc magnetic field is effective in reduction of duration of gaseous phase in arc discharge, higher variation of contact voltage in the gaseous phase which results in high frequency noise is caused. Secondly, the effect of the external dc magnetic field on the breaking arc of Ag was measured. It was found that larger current noise arises, when the contact voltage is rapidly varied at the arc discharge. There are two kinds of rapid changes, which cause high-frequency EMC problem, in the voltage waveform. One is at extinction of arc discharge. Other kind is short-duration arc (short-arc) before the ignition of the continuous metallic arc. Especially, we focused on the characteristics of the short-arc at the initial of the opening of the contact for clarifying the high frequency EMC problem. By comparing with and without dc magnetic field cases, it was demonstrated that spectrum of current noise in the case of "$B = 30$ mT" is smaller than that in the case of "$B = 0$ mT". In addition, duration and fluctuation of short-arc is suppressed by the dc magnetic field. These results are basic and useful finding to know not only the noise generation in the contact-breaking phenomena but also the material dependency for EMC problems. It is expected more experimental research on precise analysis of the voltage and current waveform have possibility to understand the phenomena of the contact and EMC problems.

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