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Frictional discharge plasma from natural semiconductor/insulator junctions: Origin of seismo-electromagnetic radiation

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Abstract

By a pin-on-disk frictional experiment simulating the motion of an asperity on a fault plane, we observed photon emissions from the gap between the quartz disk and pins made of natural semiconductor or insulator minerals during friction. The patterns and intensities of photon emissions depended significantly on the gas pressure, on the normal stress and on the shape and material of the pins. The frictional contacts made of different grain sets or ore veins can be regarded as natural semiconductor/insulator junctions arising from the difference in electron states or work functions between the contacts. During seismic activities, such semiconductor/insulator junctions in natural fault zones would generate discharge plasmas that could be one of origins of seismo-electromagnetic phenomena. Finally, in addition to its effect on the geoelectromagnetic perturbations, the significances of the discovery of discharge plasmas on geochemical reactions on a fault zone arising from tectonic activities are discussed.

Keywords: Frictional discharge plasma; Seismo-electromagnetic radiation; Semiconductor/insulator junction; Plasma process; Pin-on-disk method; Asperity

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1. Introduction

Anomalous electromagnetic radiations associated with seismic activities have been reported for a long time. A general scope of the investigations is presented in the review by Hayakawa (2001), corrective monographs edited by Hayakawa and Fujinawa (1994), Hayakawa (1999) and Hayakawa and Molchanov (2002). From the laboratory experiments of rock mechanics, possible sources of the seismo-electromagnetic emission have been related to piezoelectricity (e.g. Finkelstein et al., 1973; Nitsan, 1977), and electrokinetic effect (e.g. Mizutani et al., 1976). These two candidates require, respectively, the presence of piezoelectric minerals (e.g. quartz) and water flowing through porous rocks. That is these two mechanisms can lead to seismo-electromagnetic emissions only under limited conditions.

Regarding an earthquake as a catastrophic phenomena, from laboratory rock fracture and hypervelocity impact experiments, the generation of plasmas (Bianchi et al., 1984; Martelli et al., 1989; Crawford and Schultz, 1991, 1999), charged particles (Enomoto and Hashimoto, 1990) and charge carriers (Freund, 2000, 2002; Freund et al., 2004) in addition to the emission of electromagnetic radiation (Bianchi et al., 1984; Ogawa et al., 1985; Martelli et al., 1989; Crawford and Schultz, 1991, 1999) and light (Demin et al., 1981; Sobolev et al., 1982; Brady and Rowell, 1986), have been proposed to play a role in anomalous electromagnetic phenomena preceding earthquakes. Based on such experimental results, a theoretical model involving the propagation of plasmons in rocks has also been proposed to be at the origin of anomalous electromagnetic

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radiation from stressed rocks (Kamogawa and Ohtsuki, 1999; Ohtsuki and Kamogawa, 1999). However, these phenomena accompanying catastrophic rock failure do not seem to be applicable to the electromagnetic precursors observed before critical main shocks.

Based on mentioned above laboratory experiments, the charge densities of frictional and fracture surfaces were estimated to be the orders of 10^{-4}–10^{-2} C/m^2 (Molchanov and Hayakawa, 1995, 1998; Takeuchi and Nagahama, 2002a,b). The values estimated from the experimental results are sufficient to cause the electric discharge by dielectric breakdown of air. To clarify the discharge processes during friction, a pin-on-disk method is suitable tool to observe photon emissions; observations of photon emissions during the scratching of the surface of the disk with a pin (Miura and Nakayama, 2000, 2001; Miura et al., 2004). Using this method, Muto et al. (2005) reported that photon emissions from frictional contacts between natural rock minerals by dielectric breakdown of ambient gases due to frictional electrification. We proposed that the frictional electric discharge (plasma generation) could occur locally at microscopic asperities on fault surfaces at the onset of earthquakes, and would be the precursor of seismo-electromagnetic radiations. However, the dependences of photon distribution on frictional conditions (e.g. normal stress and gas pressure) have been unclear yet. Though the discovery of such high energy plasma may play a role in geochemical reactions arising from friction of the fault, i.e. tribo-geochemical reactions, its significance has not been also pointed out thoroughly in the former paper.

Here we report observations of photon emissions due to dielectric breakdown of ambient gas during the friction between natural semiconducting minerals (pyrite and quartz). According to the observations, we show the behaviour of photon emissions with the variations of frictional conditions (materials and shapes of pins, normal stress and gas pressure). Finally, in addition to its geoelectromagnetic effects, we also point out the significances of the discovery of discharge plasmas on geochemical reactions in a fault zone arising from tectonic activities.

2. Pin-on-disk methods

To investigate the photon emission during friction, we conducted a frictional experiment in ambient gases simulating the motion of an asperity on a fault plane by a pin-on-disk method. A schematic drawing of the instrument used to measure the two-dimensional spatial distributions of photon emission around the contact point during friction is shown in Fig. 1 (Miura et al., 2004; Muto et al., 2005). Spatial distributions and spectroscopic characteristics of photon emissions during friction were measured by an optical microscope combined with a CCD camera and a spectrometer. The CCD camera with an optical microscope and spectrometer are sensitive to photon wavelengths of 350–1200 and 200–800 nm, respectively. We observed frictional photon emissions between a quartz disk and a pin through the disk from the opposite side of the contact (Fig. 1(b)). The normal forces were varied from 50 to 150 mN and from 94 to 404 mN in experiments using quartz and pyrite pins, respectively. From the estimations of real contact area observed under an optical microscope (Fig. 1(c) and (d)), the corresponding normal stresses were estimated to be 4–12 MPa (quartz pin) and 116–870 MPa (pyrite pin). The frictional experiments were conducted under sliding velocities ranging from 10^{-2} m/s (0.1 rps) to 10^{-1} m/s (1 rps). Since argon and nitrogen gases are chemically stable and are present generally in active fault zones (Wakita et al., 1980), all experiments were performed under controlled ambient gas pressures of these gases from

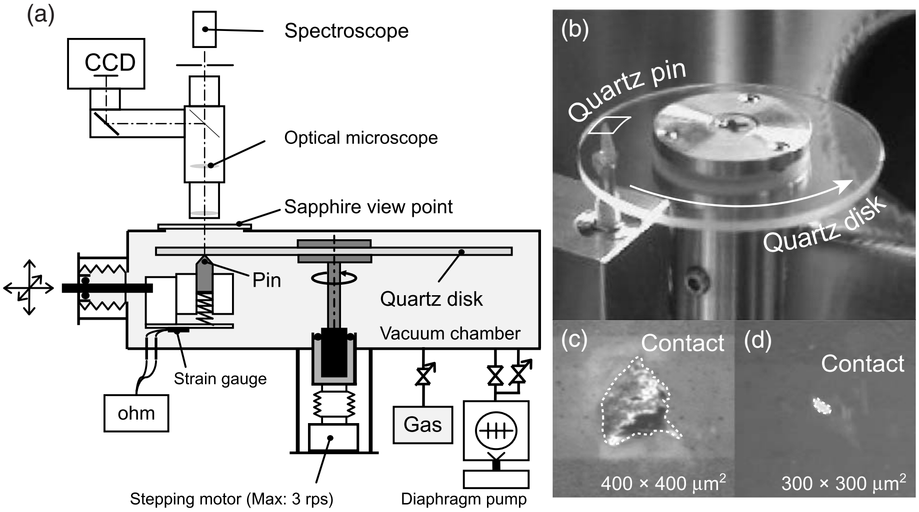

Fig. 1. Schematic drawing of a pin-on-disk method (a). Photograph of the quartz pin and quartz disk (b). Spatial distributions and spectroscopic characteristics of photon emissions during frictions were observed through the quartz disk from the opposite side of the contact by an optical microscope combined with a CCD camera and a spectrometer. Observed contact area using a quartz pin (c) and pyrite pin (d) by the CCD camera with an optical microscope. The images are the sizes of 400×400 μm^2 (c) and 400×400 μm^2 (d).

0.01 Pa (9.9×10^{-8} atm) to 4.3×10^{4} Pa (0.4 atm) under a room temperature.

During the frictional experiments by the pin-on-disk method, we utilized the natural rock minerals for materials of the disk and pins. The disk consisted of a z-cut plate of natural Brazilian single quartz (crystalline SiO_2). Quartz is the most abundant mineral in the upper crust of the Earth. The thickness and the radius of the disk were 1 and 17.5 mm, respectively (Fig. 1(b)). Both sides were polished up to optically flat, then the disk has high transmittance for emitted photons during the friction. Pins were made of same natural Brazilian quartz or of natural iron disulfur pyrite (FeS_2). We note that many seismic faults are mineralized with quartz even when the country rock is not quartz-bearing (Power and Tullis, 1989), suggesting that quartz behaviour during friction could be important for earthquakes in many rock types. It is also noted that the mineral combination utilized in our experiments (i.e. quartz/quartz and quartz/pyrite) can be seen in almost geological condition (e.g. in granitic and sedimentary rocks and in ore veins).

3. Results of microplasma observations

Fig. 2 shows representative images of frictional photon emissions from the contacts between rotational quartz disk and quartz (Fig. 2(a)–(c)) and pyrite (Fig. 2(d)–(f)) pins in ambient (argon and nitrogen) gases. The patterns of photon emissions depended significantly on the gas pressure and on the shape and material of the pins. The intensities of emitted photons also depended on the normal stresses. In Fig. 2, the areas surrounded by white lines show the contact areas observed by optical microscope (see also Fig. 1(c) and (d)). The intensities are colour scaled in arbitrary units. The directions of disk motion were right directions. Note that the images of photon emissions were sums of the

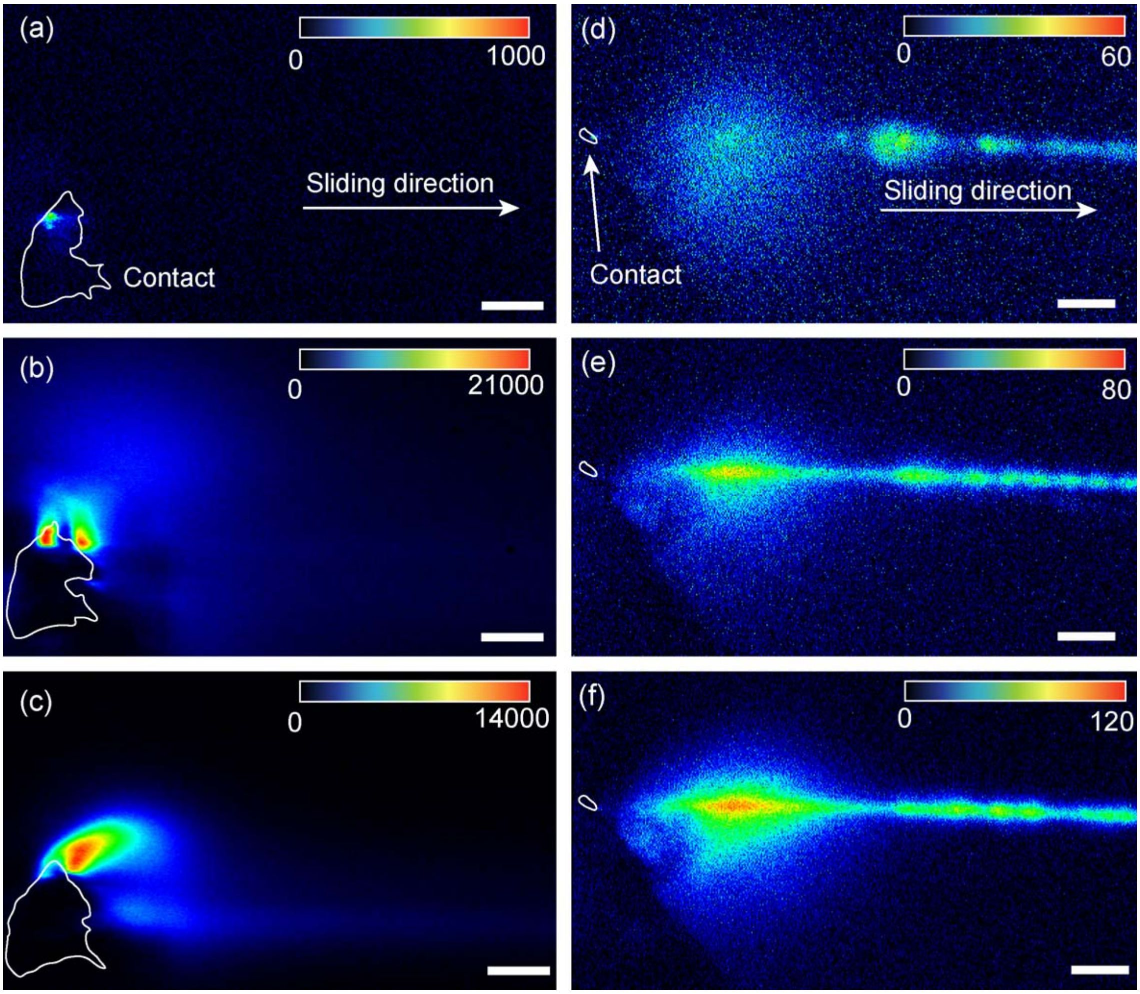

Fig. 2. Representative photon emission images during frictions using quartz (a–c) and pyrite (d–f) pins. Photon emission images using a quartz pin under normal stress $\sigma = 10$ MPa, sliding velocity $\upsilon = 102$ mm/s, nitrogen pressure < 0.01 Pa (a), nitrogen pressure $= 1.2 \times 10^{3}$ Pa (b), nitrogen pressure $= 6.0 \times 10^{3}$ Pa (c). Photon emission images using a pyrite pin under $\sigma = 120$ MPa, $\upsilon = 19$ mm/s, argon pressure $= 1.2 \times 10^{3}$ Pa (d), $\sigma = 200$ MPa (e), $\sigma = 460$ MPa (f). Note that the images of photon emissions were sums of the emissions during 100 revolutions in the case of quartz pin (a–c) and during one revolution in the case of pyrite pin (d–f). The areas surrounded by white lines are the contact areas observed by optical microscope. The intensities are colour scaled in arbitrary units. The directions of disk motion were right directions in the figures. Scale bars represent 100 μm.

emissions during 100 revolutions in the case of quartz pin (Fig. 2(a)–(c)) and during one revolution in the case of pyrite pin (Fig. 2(d)–(f)).

In the experiment using a quartz pin, intensities and patterns of photon emissions varied with nitrogen gas pressure. In vacuum (<0.01 Pa), the photon emissions were observed only inside of contact area (Fig. 2(a)), implying that thermal radiation due to frictional heating was localized in very small point inside of contact area. Under the low nitrogen gas pressure ($\sim 10^3$ Pa), the photon emissions widely occurred surrounding the contact point (Fig. 2(b)). The intensities of emitted photon observed under nitrogen gas were larger than those in vacuum. Two points of the intensive photon emissions, connecting between the contact and an intensive point outside of the contact, were observed. From frictional experiments using a synthetic quartz disk and diamond pin, since the diamond pin was found to be charged to positive and the frictional track to negative (Miura et al., 2004), this distribution represents lines of electric force due to an electric dipole generated around the contact. With increasing gas pressure up to 10^4 Pa, the intensity of photon emissions decreased and its pattern concentrated around the pin (Fig. 2(c)). Above relatively higher pressure ($\sim 10^4$ Pa), the highest intensities of emitted photons were recorded outside of contact area (Fig. 2(c)).

In the experiment using a pyrite pin, the photon emissions showed the similar patterns to ones using the quartz pin; comet-like distributions. The photon emission occurred at narrow tails of around 800 μm long due to small contact area compared with the quartz pin. The intensities of emitted photons increased with increase in normal stress, while the patterns of emitted photons did not change with normal stress (Fig. 2(d)–(f)). As observed during the friction using quartz pin, the highest intensities of emitted photons were recorded outside of contact area, implying that the photons were generated at a gap of a certain width between the disk and pins. In this experiment, the intensities of photon emissions using the quartz pin were generally higher than those using pyrite one. Moreover, the normal stresses found to observe the photon emissions using pyrite pin were about one order of magnitude larger than those using quartz one. These two results on the photon intensity may be responsible for the small contact area of the pyrite pin used in this experiment compared with the quartz one.

From spectral analyses, Muto et al. (2005) clarified that the emitted photons between natural rock minerals were caused by dielectric breakdown of ambient gases due to frictional electrification, indicating the generation of discharge plasmas during friction. The plasmas arising from a dielectric breakdown of ambient gas as observed in this study is similar to one observed during friction between a diamond pin and insulator disks (Si_3N_4, Al_2O_3, ZrO_2 and soda-lime glass) in air (Miura and Nakayama, 2000, 2001). However, it is quite different from plasmas induced by hypervelocity impacts (Bianchi et al., 1984; Crawford and Schultz, 1991, 1999) and catastrophic collapse (Martelli et al., 1989) accompanying the vaporization and ionization of rock fragments or dusts. It is also different from plasmons in rocks (Kamogawa and Ohtsuki, 1999; Ohtsuki and Kamogawa, 1999), which have previously been proposed to be the sources of the electromagnetic precursor of earthquakes based on experimental studies on exo-electron emission by Enomoto and Hashimoto (1990).

4. Discussion

From the frictional experiment simulating a shearing of an asperity on a fault plane, we clearly showed the dependence of patterns of discharge plasmas on the gas pressure and on the shape and material of the pins (Fig. 2). The mineral contacts which generate the frictional discharge plasmas (i.e. quartz/quartz and quartz/pyrite contacts) can be regarded as semiconductor/insulator junctions seen in almost any geological condition. Even in the contact between nominally similar insulators, the charge was known to be generated if trapped holes and electrons on newly fractured surfaces are excited to the valence or conduction bands (Takeuchi and Nagahama, 2002a,b). For example, quartz/quartz contact causes electrification depending on surface electron and hole trapping states, i.e. electron states of surface (Iwamatsu, 1986; see also Takeuchi et al., 2004). In addition, pyrite (FeS_2) and other sulphide minerals exhibit either n-type or p-type semiconducting behaviour due to their chemical compositions (e.g. sulphur/iron ratio, arsenic content) and formation temperatures (Abraitis et al., 2004). Within a pyrite aggregate, there may exist zones exhibiting alternate n- and p-type behaviour. Thus, different grain sets or ore veins including such minerals would become natural semiconductor/insulator devices (e.g. diode, transistor, metal-oxide-semiconductor devices) arising from the difference in electron states or work functions between the contacts (Demin et al., 1981, 2004; Sobolev et al., 1982; Iwamatsu, 1986; Freund, 2000, 2002; Takeuchi and Nagahama, 2002a,b; Abraitis et al., 2004; Freund et al., 2004; Takeuchi et al., 2004). During seismic activities, such semiconductor/insulator junctions in natural fault zones would electrify and ionize the gaseous body existed between fault asperities, then generate discharge plasmas that could be one of origins of seismo-electromagnetic radiations.

Muto et al. (2005) estimated the potential difference generated by frictional electrification to be about 34 V that gives the surface charge density of 5.5×10^{-5} C/m^2. Although our experiments were conducted under lower stress ($\sigma \sim 4$ MPa) and sliding speed ($\upsilon \sim 10^{-2}$ m/s) than the conditions of previous fracture or hypervelocity impact experiments, the charge density is roughly same orders of magnitude measured in previous experimental results (10^{-4}–10^{-2} C/m^2: Molchanov and Hayakawa, 1995, 1998; Takeuchi and Nagahama, 2002a). Since the fracture shear stress is ~ 1.3 times larger than the frictional one in Westerly granites (Byerlee, 1967), the mechanical strain energy of the former which would be an input for electromagnetic emissions is ~1.7 times larger than the latter under elastic deformation. So, the generation efficiency from the frictional discharges would be rather higher (~1.7 times) than that by the microfracturing model based on the emission from the microcurrent during fracturing (Molchanov and Hayakawa, 1995, 1998). Moreover, because the polarization characteristics of the discharge have been known to be explained by the theory of half-wave dipole antenna (Hoshino et al., 1999), its power gain sub-parallel to fault planes is slightly larger than that of the microfracturing model (Molchanov and Hayakawa, 1995, 1998). However, the area of real contact area is generally smaller than that of apparent contact area. So, from the view point of the charge distributions on frictional surfaces, we further should investigate the generation efficiency of electromagnetic waves from discharges and microfracturings.

In addition to its influence on geoelectromagnetic disturbances, we believe that the frictional discharge plasma is a reasonable origin of geochemical reactions on fault surfaces through plasma processes. For example, Enomoto and Zheng (1998) and Enomoto et al. (2001) found hard foliated and magnetized gouge near the Nojima Fault zone, north-west of Awaji Island (the fault of the 1995 Hyogo-ken Nanbu earthquake $M = 7.2$; $15 \times 40\ \mathrm{km}^2$ of fault plane area), where an earthquake light was witnessed (Tsukuda, 1997). From a spark plasma sintering experiment, they pointed out the possibility of earthquake lightning-induced sintering of the gouge to make it harden within 10 s at an approximate current of 1000 A and voltage of 10 V DC. From our discovery of the frictional discharge plasma during friction, the hardening of the gouge found in Hirabayashi (Enomoto et al., 2001) might be due to the sintering densification by frictional discharge plasmas. When a pulse of such discharge occurs on the fault surfaces, the value of discharge current would be up to 1000 A. The potential difference and discharge currents are equivalent to cause densification of the gouge (Enomoto et al., 2001). If a seismic motion will continue about 10 s, the discharge plasma could harden the fault gouge by spark plasma sintering processes. The presence of the plasmas on fault surfaces during seismic activities would be also cause of other tribo-geochemical reactions, including plasma deposition, sputtering, and polymerization, atomic and radical reaction (e.g. Wakita et al., 1980) in the plasma. The role of these processes needs to be further investigated to clarify the mechanisms initiating geochemical reactions within fault zones arising from seismic activities.

5. Conclusions

By the pin-on-disk frictional experiment, we observed photon emissions from the gap between the quartz disk and pins made of natural semiconducting minerals (quartz and pyrite) during friction. The patterns of photon emissions depended significantly on the gas pressure and on the shape and material of the pins. The intensities of emitted photons also depended on the normal stresses. The frictional contacts observed the plasma generations can be regarded as natural semiconductor/insulator junctions arising from the difference in electron states or work functions between the contacts. During seismic activities, such semiconductor/insulator junctions in natural fault zones would electrify and ionize the gaseous body existed between fault asperities, then generate discharge plasmas that could be one of origins of seismo-electromagnetic phenomena. Finally, in addition to its effect on the geoelectromagnetic perturbations, we pointed out the significances of the discovery of discharge plasmas on geochemical reactions on a fault zone arising from tectonic activities.

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