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S. SENGOKU, T. MATSUDA, H. MATSUMOTO,
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K. ODAJIMA, H. KIMURA and Y. SHIMOMURA

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Japan Atomic Energy Research Institute

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Seio SENGOKU, Toshiaki MATSUDA, Hiroshi MATSUMOTO, Hideo OHTSUKA, Takashi ARAI, Kazumi OHASA, Shin YAMAMOTO, Kazuo ODAJIMA, Haruyuki KIMURA and Yasuo SHIMOMURA

Division of Thermonuclear Fusion Research,
Tokai Research Establishment, JAERI

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Three types of carbon surface, i.e. pyrolytic graphite (P.G.), carbon films produced by rf sputtering and by methane discharges, were tested as limiter surfaces in a tokamak. Arcing and serious erosion are observed on the surface produced by rf sputtering even in a stable discharge. Arcing is observed on the P.G. surface and the carbon surface produced by methane discharges, only in an unstable discharge. Chemical sputtering is the dominant process for carbon efflux at the high temperature limiter surface. It can be easily suppressed, however, by pre-bombardment at the high temperature. Ion sputtering is the main process for carbon impurity production. It is concluded that the carbon surface prepared suitably is promising for the first wall in a fusion reactor.

Key Words: Tokamak, Limiter Surface, Sputtering, Carbon films
Pyrolytic Graphite, Arcing, Erosion

カーボンリミタ表面の特性とそのケミカルスパッタリング抑制

日本原子力研究所東海研究所核融合研究部
仙石盛夫・松田俊明・松本 宏・大塚英夫
新井 貴・大麻和美・山本 新・木村晴行
小田島和男・下村安夫

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①パイロリティック・グラファイト，② RF・スパッタリング法により作られた炭素膜，③メタン放電により作られた炭素膜の三種の炭素表面がトカマクにおけるリミター表面として試験された。②の炭素表面では，安定な放電条件下でもアークと損傷が観察された。①と③の表面では，不安定な放電下でのみ，アークが起きるのがわかった。高温時のリミター表面から出る炭素不純物束は，主にケミカルスパッタリングによるものであることがわかった。しかしこのケミカルスパッタリングは，高温状態でプラズマ中にさらし，イオンで表面をたたくことによって，容易に抑制することが出来た。イオンスパッタリングが炭素不純物生成の主要因であった。これらの結果から，適切な方法によって作られた炭素表面は，核融合炉の第一壁として有望なものであるといえる。

CONTENTS

1. Introduction

Carbon is attractive for the first wall in a reactor because of the following reasons.

a) Radiation loss from low-z impurities is rather small in a high temperature plasma.

b) Thermal properties are as good as those of Cu, Mo, or W.

c) The yield of the self sputtering, which is the most important process for impurity origins[1),2)], is smaller than the high-z material such as Mo. Therefore, the wall erosion is rather low[3)].

Carbon surface, however, has not been investigated in detail as the first wall of tokamak devices. And the following problems have been pointed out.

a) Chemical sputtering and arcing

b) Formation and maintenance of the clean carbon surface

The chemical sputtering yield is much higher than the physical sputtering yield at around 500°C. Therefore, the carbon cannot be employed as the first wall of a reactor whose temperature is around 500°C, if the chemical sputtering cannot be suppressed.

Arcing is observed on metal surfaces in tokamaks but is only induced in a unstable discharges or in a unstable phase of a normal discharge, e.g. startup phase[1)]. Also arcing is very sensitive to the wall condition. These results suggest that arcing may rather easily occur on the certain kinds of the carbon surface[1)]. Therefore it is necessary to obtain a carbon surface on which arcing is not serious. The most promising method to obtain a clean surface is in-situ coating which is usually employed for metal coating such as titanium[4)] or molybdenum[5),6)] gettering.

The other problem may be the pulverization which was observed after many discharges. The pulverized surface may not be reliable and arcing may be easily induced.

In order to investigate these problems, the following three kinds of carbons are tested as the limiter surface:

1) Pyrolytic Graphite (P.G.),

2) Carbon film produced by rf sputtering method[5)],

3) Carbon film produced by methane discharges.

These three kinds of carbon are employed by the following reasons: P.G. is considered as the ideal wall; the carbon produced by rf sputtering similate the pulverized carbon; and the carbon produced by methane discharges is the carbon produced by an easy in-situ coating.

2. Experimental Results

Figures 1, 2 and 3 are SEM pictures of three kinds of the carbon. The carbon produced by rf sputtering has the form similar to powder. The carbon produced by methane discharges is rather similar to the P.G. surface. In the methane discharges, the carbon ions which flow onto the surface have energy of about 100 eV because they are accelerated by the sheath potential. Thickness of a few Å on the limiter surface is obtained by one discharge. The discharge current is 20 kA, the duration is 30 ms and the filling methane pressure is 1×10^{-4} Torr.

The standard method to investigate sputtering and arcing on a surface contacting to a plasma is used[1]. A part of the limiter is biased. The current to the limiter and the intensity of CII line radiation near the limiter are observed. The emitted carbon from the limiter is ionized within 100 μsec. Therefore the intensity of CII line is proportional to the efflux from the limiter surface. Figure 4 shows the results. Arcing is frequently observed on the carbon surface produced by rf sputtering, e.g. the probability of arcing is 17 % with 400 V of applied voltage. This situation simulates the surface which contacts to the plasma with $T_e \approx 200$ eV. Arcing is observed only in disruptive discharges on the P.G. surface and the carbon film produced by methane discharges. This result is very similar to those of metal surfaces[1]. Figure 5 shows ΔI_{CII} v.s. V where ΔI_{CII} is increment of CII line intensity and V is bias voltage. This figure shows the efflux of C is due to the proton sputtering. Therefore the ion sputtering is the dominant process of the carbon impurity origin.

The next problem is a chemical sputtering at a high temperature regime. The part of the limiter is heated up to 750°C and the standard method is employed to measure the relative sputtering yield. Figure 6 shows sputtering yield is enhanced by the chemical sputtering with $T_{limiter} \gtrsim 250°C$. However, the enhancement by the chemical sputtering can not be observed on the surface which was bombarded by protons at a high temperature (Fig. 7(a),(b)). Therefore the chemical sputtering is easily suppressed. A similar result is also obtained by T. Abe et al[7].

3. Conclusions

The following results are obtained.

2. Experimental Results

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3. Conclusions

The following results are obtained.

1) Carbon film is easily produced by methane discharges, i.e. the surface can be easily refreshed. The surface has good characteristics as mentioned below.
2) Arcing is observed only in unstable discharges on P.G. surface or on the carbon film produced by methane discharges and this result is similar to that of a metal.
3) Ion sputtering is the dominant process of carbon impurity efflux from the carbon limiter.
4) Chemical sputtering is easily suppressed.

5) Arcing is frequently observed on the carbon film produced by rf sputtering method.

These results encourage the attempt to employ carbon for the first wall in a reactor. Carbon surface, however, may be easily pulverized and the powder carbon would create serious problems, i.e. arcing is easily induced with a scrape-off layer plasma of $T_e \approx 200$ eV. Therefore it is necessary to develop a method of removing powder carbon.

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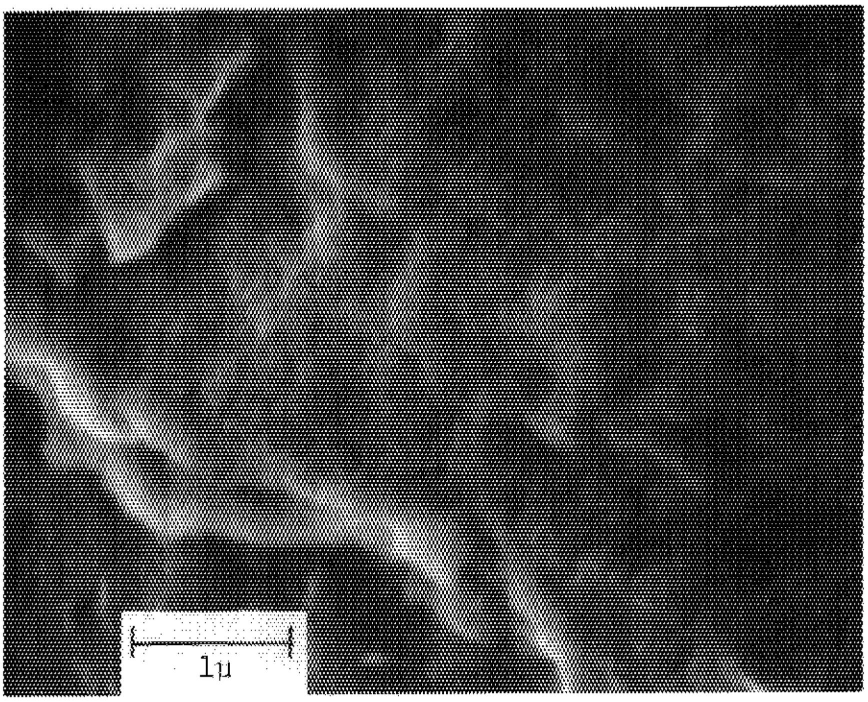

Fig. 1 Scanning electron microscopic (SEM) picture of pyrolytic graphite surface.

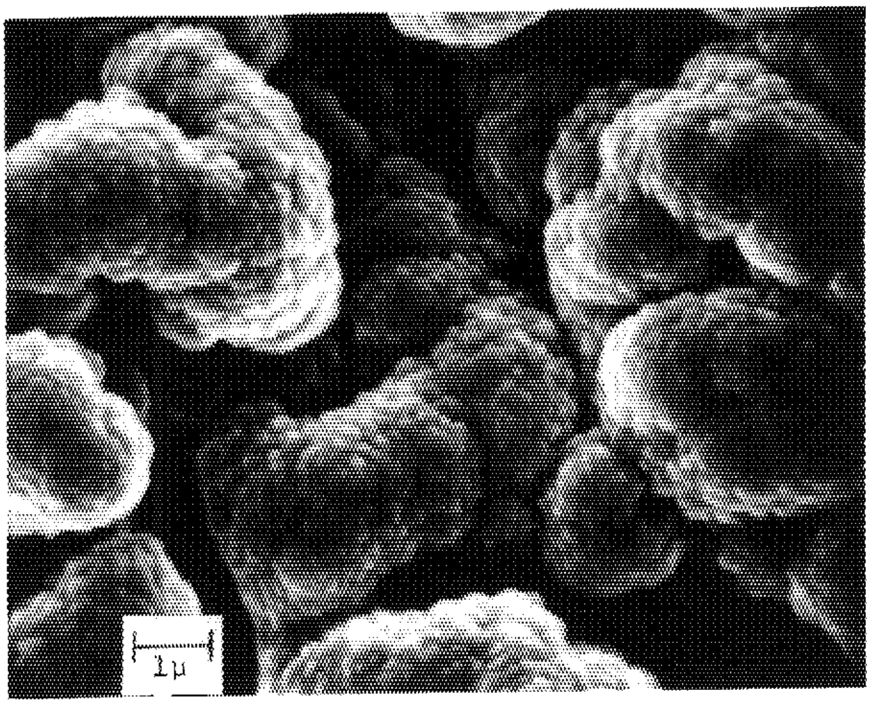

Fig. 2 SEM picture of carbon surface produced by rf sputtering method.

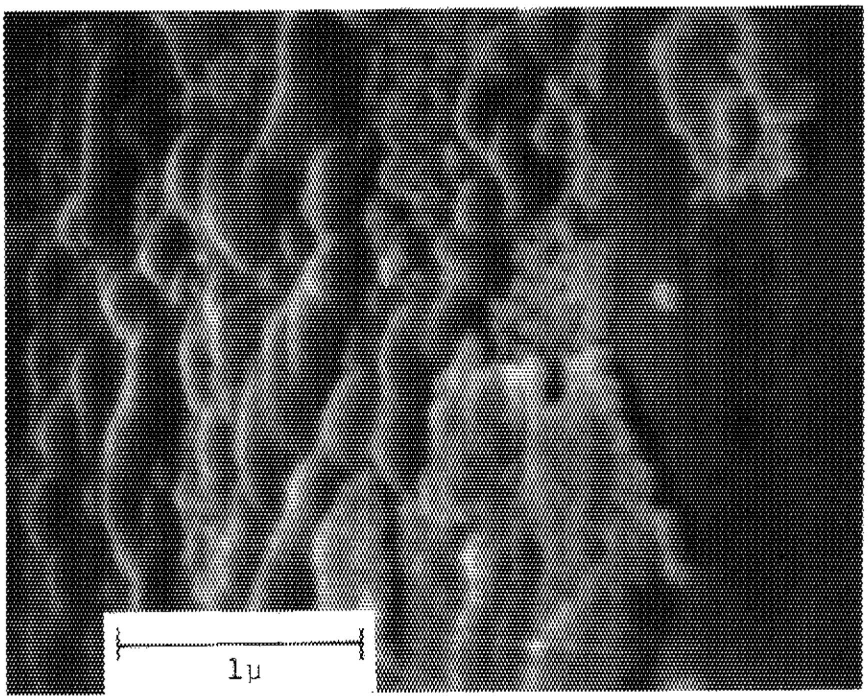

Fig. 3 SEM picture of carbon surface produced by methane discharges.

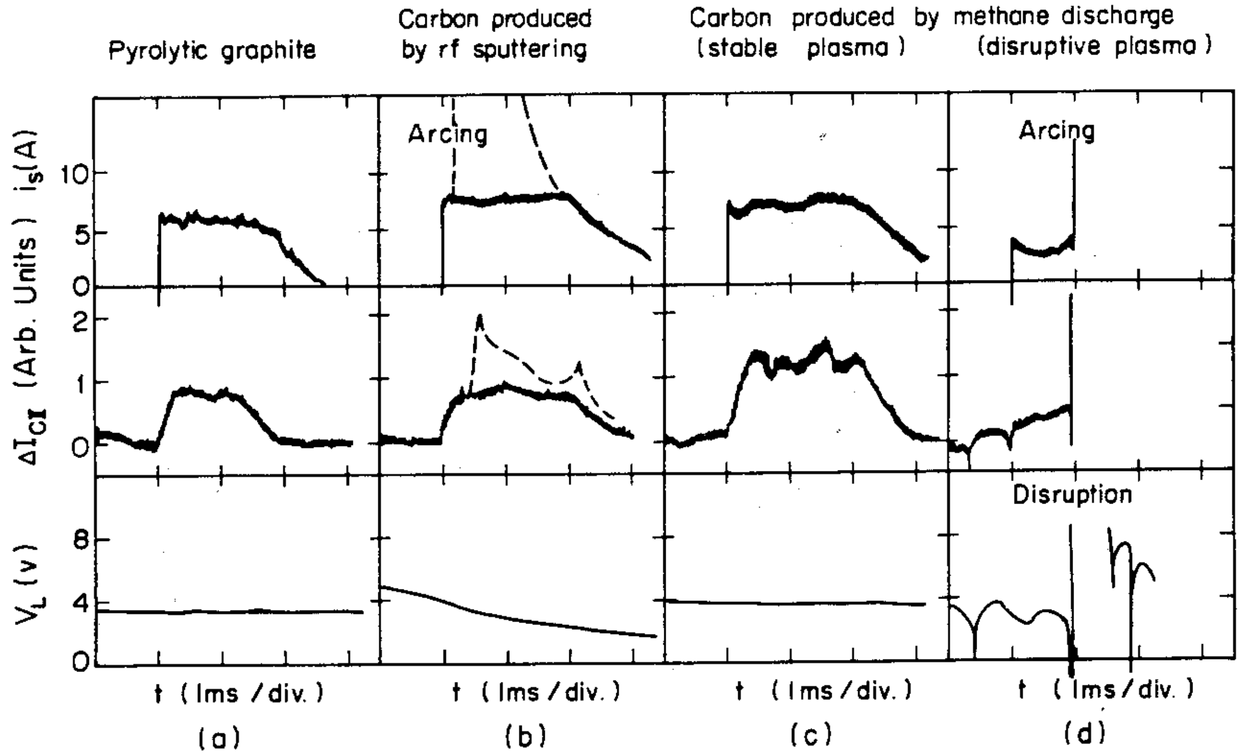

Fig. 4 Typical wave forms of ion saturation currents i_s of a part of the limiter, increment of CII line intensity ΔI_{CII} and loop voltage V_L

(a) Pyrolytic graphite.

(b) Carbon surface produced by rf sputteing method. Arcing is observed.

(c) Carbon surface produced by methane discharges.

(d) Carbon surface produced by methane discharges in a disruptive discharge. Arcing is observed.

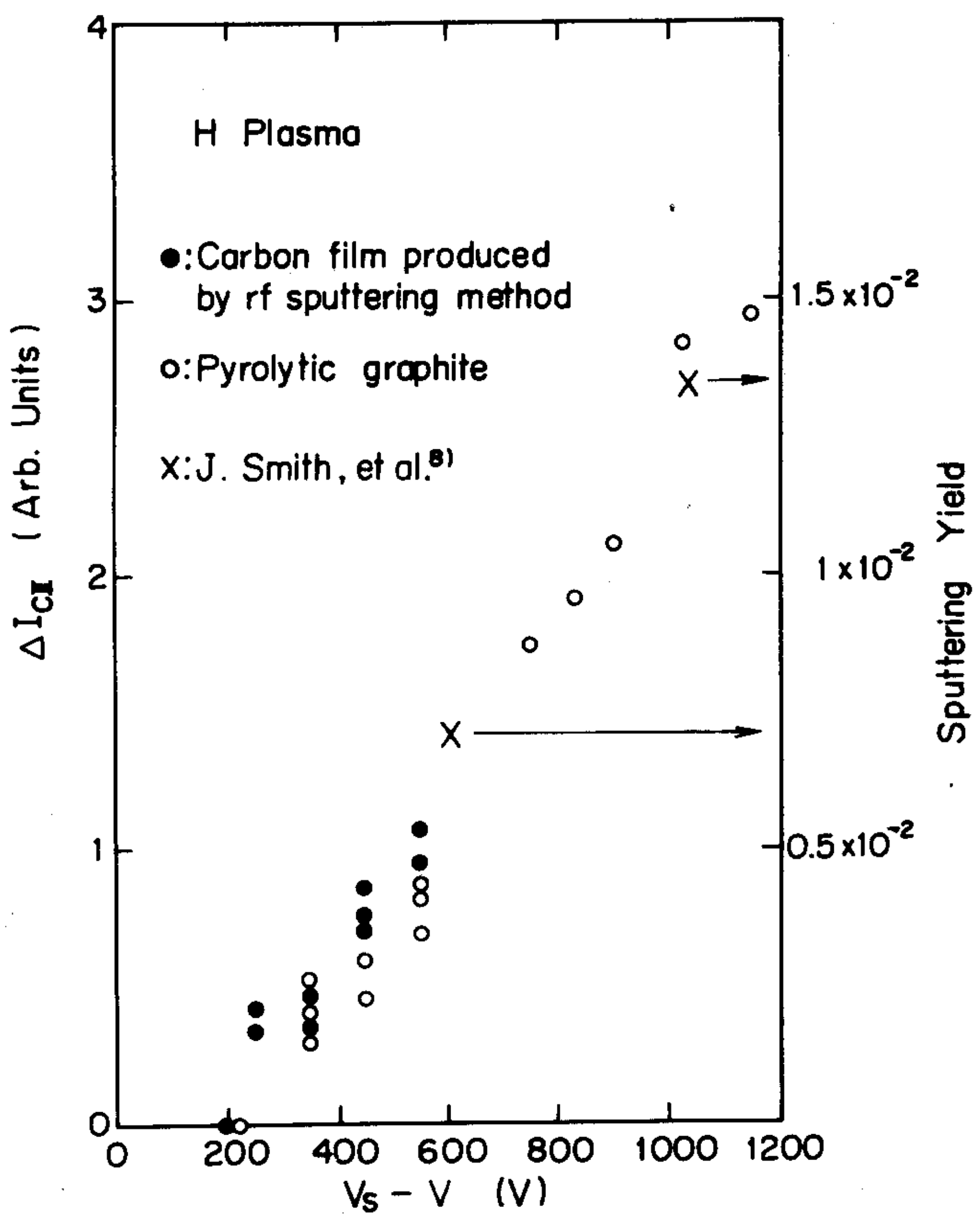

Fig. 5 ΔI_{CII} v.s. V where ΔI_{CII} is increment of CII line intensity and V is bias voltage.

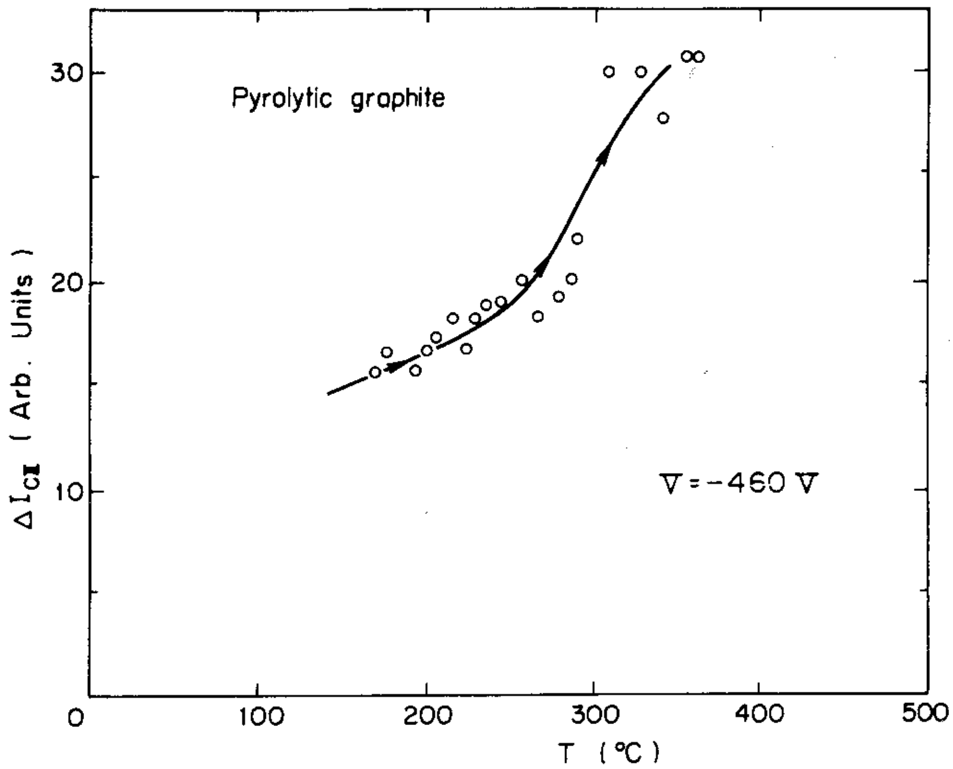

Fig. 6 ΔI_{CII} v.s. T where ΔI_{CII} is increment of CII line intensity and T is temperature of a limiter surface.

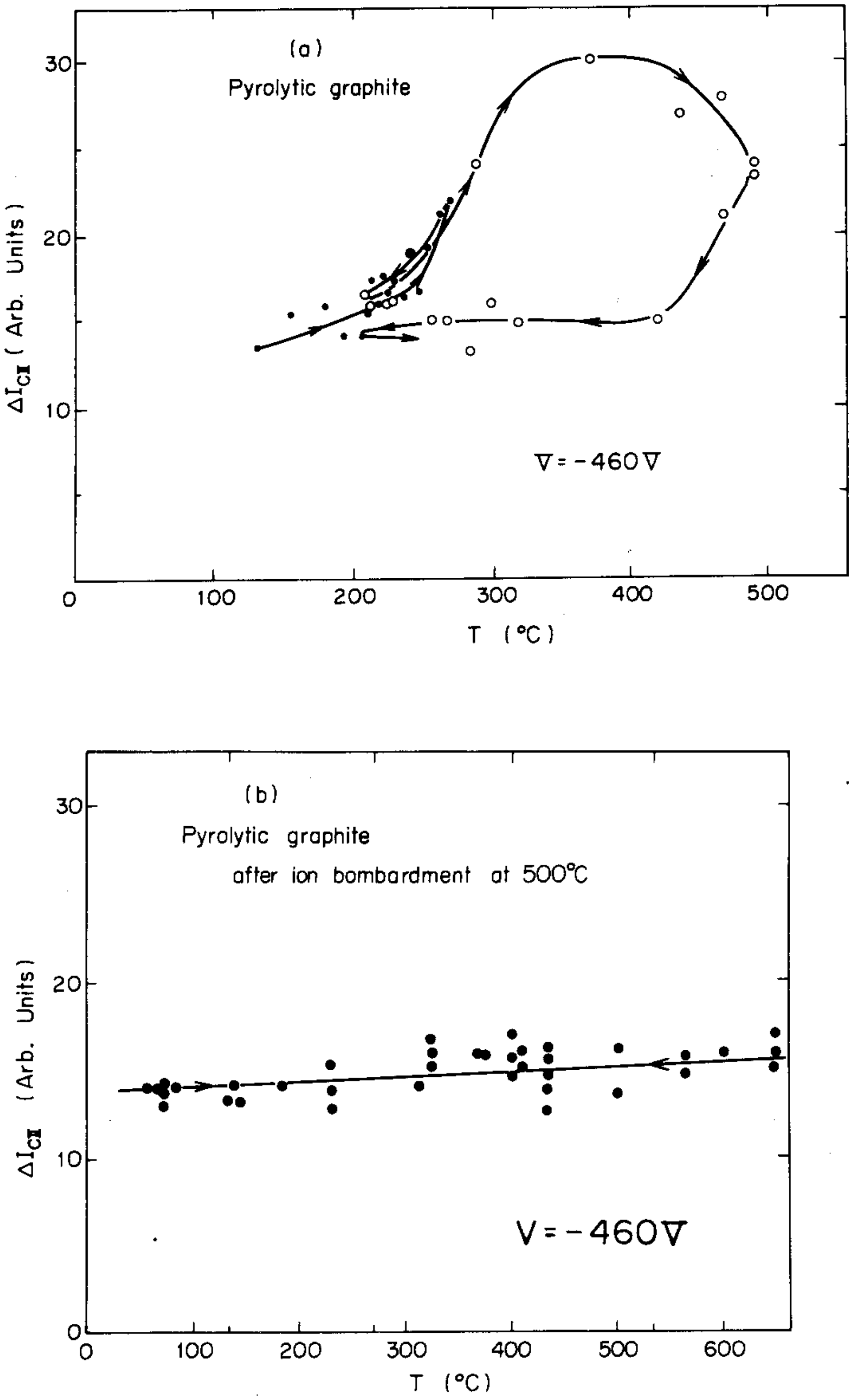

Fig. 7 ΔI_{CII} v.s. T. Suppression of chemical sputtering is observed after (a) one heat cycle; (b) a few heat cycles, with ion bombardments.