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Practice-Oriented Engineering Education: Introducing COMSOL Multiphysics Software to Printed Electronics Course

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Abstract **Original Research Article**

Printed electronics are stealing attraction in education and study and sharing wide range of market due to capability of flexibility, wide-area, low-cost, eco-friendly and mass-producing. However, printed electronics course is appearing as a temporary challenge to student who are major in typical Microelectronics. It is mainly caused from that printed electronics course is dependence of printing tools and organic materials which differ from typical principle of silicon based electronics, and thus many errors are appearing in student design and manufacturing. For the one route to deal these errors, in the printed electronics course, COMSOL Multiphysics software which can simulate operating characteristics of electronics devices is combined with our typical education of printing tools and organic materials. Comparisons are of between improved course and typical course of same period. For the same periods, in the improved course which is combined with simulation software, periods of each sections of course are compressed than typical course. According to a comparison result, by combining simulation software, final grades of student who educated from improved course are higher than that of student who educated from typical course(without of the simulation software) and it is founded that the new improved course stimulate student's creativity and encourage enthusiasm for study.

Keywords: COMSOL Multiphysics Software, Printed Electronics Course, Under-graduating Student, Microelectronics.

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1. Introduction

Printed electronics is an electronic science and technology based on conventional printing techniques as the means to manufacture electronics devices and systems.

To most people, "Printed electronics" is an unfamiliar phrase. Even experts in electronics may not have heard it. Many people may have it confused with conventional printing technology or mixed up with electronic printing. The aim of printed electronic s is to make integrated electronic systems using printing technol ogy instead of much more expensive and complex IC manufactu ring technology.

Now according to printed electronics courses presented in som e universities, introduction to printed electronics, development t rend, printing tools and equipment are only consisted in their co urses. Thus, challenges are appearing in printed electronics stud y for Microelectronics student, who is far from material science student. For detail, silicon based Microelectronics students are i n difficult to understand various organic materials which are unf air with inorganic materials, also those students have less knowl edge of printing based manufacturing than etching based manuf acturing, thus the students have temporary challenges during pri nted electronics course. The students of microelectronics are wo rking on the printed electronics curriculum to develop a knowle dge of the interdisciplinary field and to tackle complex technical tasks in the future. It is also essential to develop this field by tea ching printed electronics to students in the current undergraduat e field, in the context of the development of a specialized, indep endent course in printed electronics.

Printed electronics uses a variety of methods, including traditi onal printing techniques. The general manufacturing principle is to use various functional inks to print the desired patterns on the substrate in layers and then to ripen the material through drying and heat treatment.

Then, a variety of packaging techniques are introduced to prot ect against external environment.

As such, the printed electronics are referred to as the base mat erial, including substrate material, conductive material, semicon ductor material, dielectric material, magnetic material, and insul ating material, while the printing techniques include spin-coating, screen printing, offset printing, inkjet printing, etc. The basic materials can be prepared in ink form or as organic polymer materials that have attracted attention due to their environmental friendliness. It is important to achieve performance above previously used electronics and to reduce manufacturing costs reasonably. It also develops its own characteristics, including flexibility and transparency. The fabrication of devices in printed electronics is in some cases superior to silicon-based technologies because this is an additive process and also because of the freedom of substrate selection. Figure 1 shows the cost-performance relationship between printed electronics and silicon-based microelectronics.

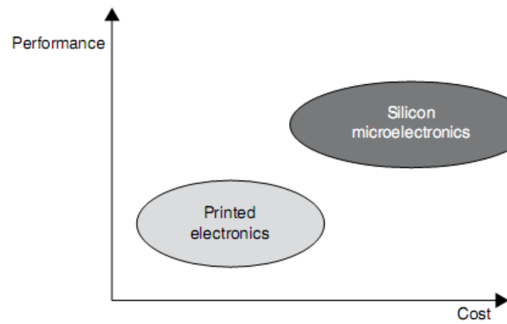

Figure 1. Printed electronics versus silicon-based microelectronics

As shown in Fig. 1, the performance of silicon-based microelectronics is currently in a poor state, but the prospect is promising due to the high cost and wide range of materials used. In other words, many countries have continued to develop this field and have made great progress in their respective education. Typically, as mentioned in [1], a practical focus on organic electronics courses has been achieved. For example, they introduced the "organic and printed electronics educational environment" and conducted experiments by providing the detailed process and technology needed to build it. The experiments were carried out using a computer-aided design and characterization via fabrication. Using this device, we expect to be practically oriented in the future of students' organic and printed electronics education. In addition, the authors [2] mentioned that the organic electronics laboratory course of postgraduate students was implemented to improve their knowledge and practical ability. Similarly, in other areas other than printed electronics, the incorporation of programming logic into the digital electronics curriculum has improved student outcomes [3].

The challenges occurred for teaching "Printed electronics" subject to Microelectronics student are following:

- Due to confusion between "Printed electronics" subject and traditional printing technique for publishing, course choice rate of printed electronics among Microelectronics students is falling, whereas other students who are not related with electronics are paying attention to the course choice. Thus, it takes a lot of time to recognize the basic theory of printed electronics for microelectronics student who choose this course.
- The cognition rate are falling because of lack of basic concept about ink preparation, printing technique and packaging skill.

This paper demonstrate the development of printed electronics course for Microelectronics student by educating basic theory, simulating operating characteristics and optimizing geometries of electronic devices with COMSOL Multiphysics before manufacturing the devices by printing technique.

2. Introducing simulation software to printed electronics course

2.1. Group study

Each group implemented previous study for 6h and announced study result by the means of discussion. The followings are the content of group study.

- Success from previous study on NO_2 gas sensor

For gas detecting, gas sensor base on electrochemical behavior is sensitive to electrical current which occurs when oxidation and reduction of target gas in electrode. Now development of sensor is focused on improving characteristics of selectivity, sensitivity, repetition and fast response [4, 5]. For reach these improvement electrode material and electrolyte material are the main factor. Up to date as an electrode material, gold nano-particle, copper nano-particle are adopted widely [6-9]. Electrochemical sensor can be classified as liquid sensor with only liquid electrolyte, semi-solid sensor with both of solid poly-composited electrolyte (Nafion) and liquid electrolyte, also fully solid state sensor with solid poly-composited electrolyte according to adopted electrolyte. For electrolytes of sensor, liquid electrolytes such as H_2SO_4, KOH, KCl, and inorganic conductor material such as YSZ and NASICON, room temperature ionic liquid electrolyte such as $[C_4mpy][NTf_2]$ [10-16], also more importantly the Nafion film [11, 18-20] are used widely.

- Deficiency of previous study

Liquid based electrochemical sensor has some defects due to leakage and waste of electrolyte material and decreased sensitivity resulted from the leakage and waste. So solid based sensor is developed for eliminating these defects [21-23].

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Inorganic conductor based sensor has a defect of low adsorption/desorption characteristics and low temperature operation. Also room temperature ionic liquid electrolyte has a defect to interrupt diffusion of gas to electrode due to own viscosity. The most typical and important thing is the study on development electrochemical gas sensor based on Nafion film. The Nafion film has high ionic conductivity and mechanical strength

- Improvement

We are going to design and simulate a fully solid-state electrochemical NO_2 gas sensor with 3-electrode system by using COMSOL Multiphysics, engineering analysis software widely used. The model of sensor used in simulation is drawn 3-dimensional. As the simulation results, we are going to obtain the current density of the electrolyte. And then we are going to perform an experiment for the testing of suggested sensor. In other words, we are carring out the simulation concerned with bias voltage, operating temperature and relative humidity, and pre-treated solvents for H_2SO_4, KOH, KCl in the electrochemical NO_2 sensor based on polymer electrolyte, Nafion membrane. And then we will give simulation results through the testing. The results in both simulation and experiment are compared each other.

- Simulation result and experiment plan

Fig.2 shows the 3-D Model of the sensor that are used in the simulation.

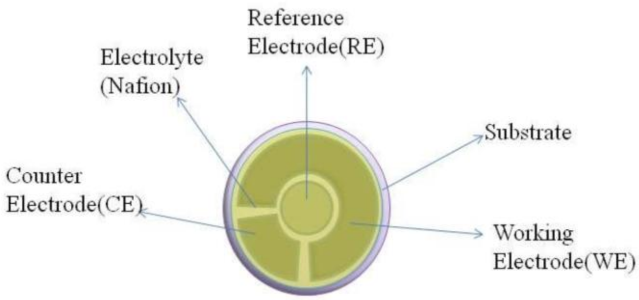

Figure 2. Electrode structure of NO_2 gas sensor using solid-state electrolyte.

The model of sensor in simulation mainly consists of substrate, working electrode, counter electrode, referenced electrode and electrolyte-Nafion membrane. The substrate is 4mm in radius, the electrodes are $15mm^2$, $5mm^2$ and $10mm^2$ in area respectively. And electrode thickness is 0.05mm for all the electrodes and the thickness of electrolyte is set in 0.17mm, of Nafion 117 membrane. For the simulation, a bias voltage in the range of 0.1-1.5V with an interval 0.1V is applied to working electrode versus reference electrode, containing the redox potential of NO2 (0.9V). It is set in temperature of 20-80℃ with an interval 10℃ and relative humidity 20-100% RH with an interval 20%. Simulations depending on the different pretreatment solvents are performed by setting conductivity of pretreated Nafion membrane with that each one respectively.

Fig. 3 shows the 3D diagram and meshed state of the sensor in the working interface of the simulation software. The number of mesh elements was 33, 651 domains, 16, 629 boundary and 1, 165 edge elements.

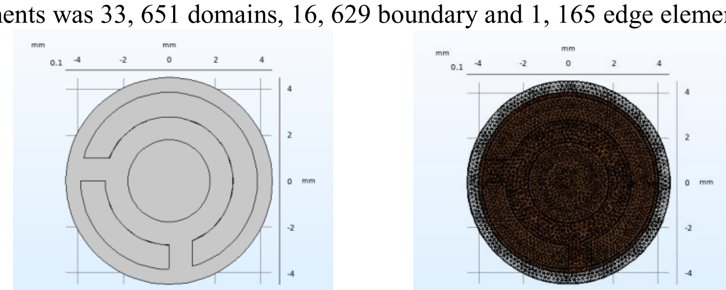

Figure 3. The 3D diagram and the meshed state of sensor

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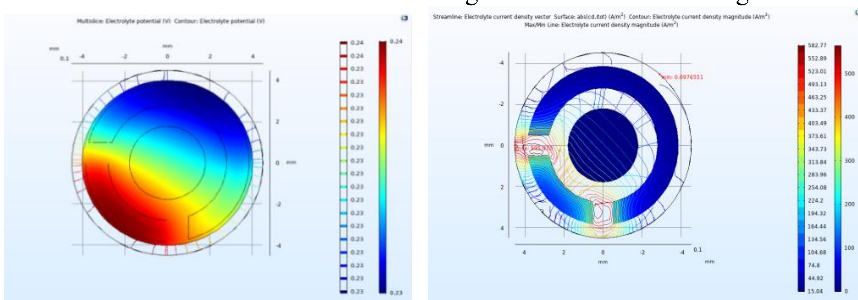
The simulation results with the designed sensor are shown Fig. 4.

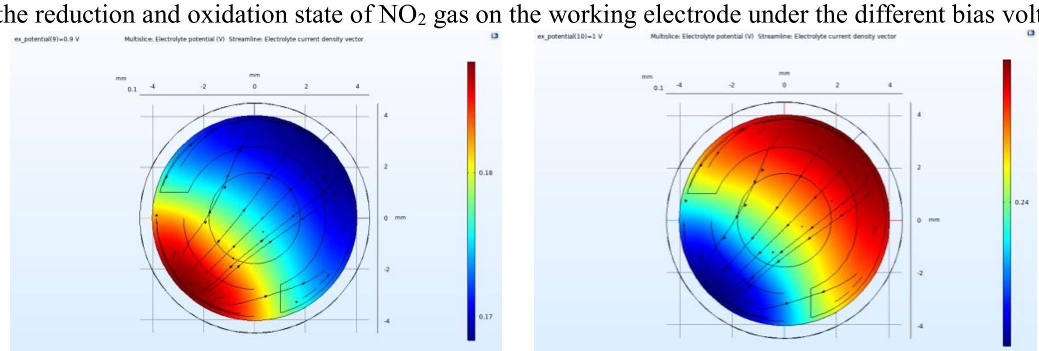


(a) (b)

Figure 4. Simulation results showing the potential and current density of the sensor electrolyte (a) potential of the electrolyte, (b) current density of the electrolyte.

Fig.4 (a) is a picture, drawing the potential of the electrolyte in the sensor. The potential at the side of counter electrode is higher than the others, which is due to the higher concentration of protons, is generated from the oxidation reaction of water on it. Simultaneously the NO_2 gas is reduced by receiving proton and electron at the working electrode. Protons are transmitted from the counter electrode to working electrode through the solid state electrolyte and electrons are conducted through external circuit. And Fig. 4 (b) shows the current direction and the contour plots of the current density of the sensor

Fig.5 shows the reduction and oxidation state of NO_2 gas on the working electrode under the different bias voltage applying.



(a) (b)

Figure 5. The reduction state and oxidation state of NO_2 gas on the working electrode (a)- reduction reaction state, (b)- oxidation reaction state.

As shown in Fig.5, the color of the electrolyte potential for the side of working electrode changed from blue to red at 0.9V and 1.0V applying. The standard redox potential of NO_2 gas is 0.99V, therefore we can understand it will be oxidized below 0.99V (bias voltage), but it will be reduced above that point. Alternating color in the picture describes the redox mechanism. In other words, during the oxidation reaction on the working electrode, there will be reduction reaction on the counter electrode at the same time. The Current-Voltage characteristics of the sensor is shown Fig. 6.

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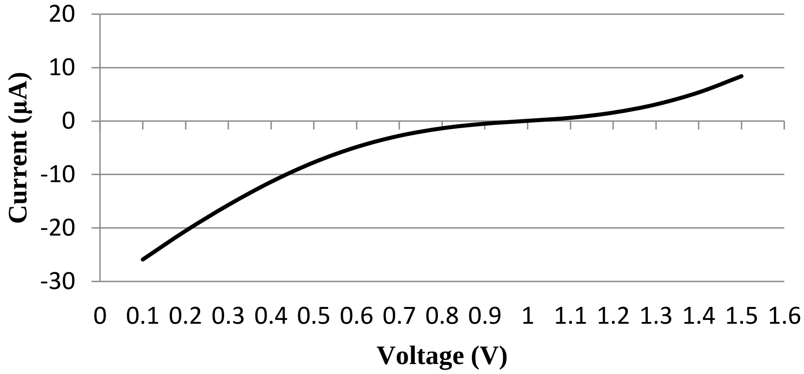

Figure 6. Current-Voltage characteristics of the sensor (simulation)

As shown fig. 6, sensing current increases as the bias voltage increases. Current-Voltage characteristics reflect the stability of the sensor with the increase or decrease of the bias voltage during it operates. As shown fig. 6, the current plot presented a gentle slope from 0.6V to 1.3V, therefore we can get a stable current with applying voltage within above-mentioned range. Simulation was also performed to consider the current with the change of operating temperature. The temperature (T) was increased by 5℃ at a time in the interval 20~80 ℃.

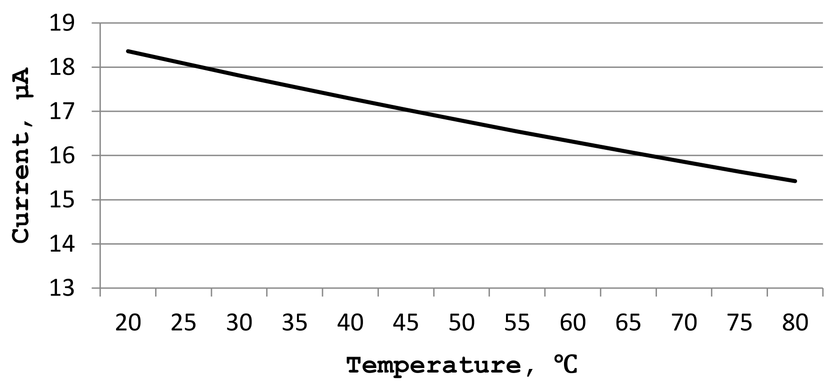

Figure 7. Current-Voltage characteristics with increase in operating temperature

Table 1. Water content and conductivity of Nafion membrane depending on the relative humidity.

Relative Humidity (RH, %)	Water content (wt, %)	Conductivity (S/m)
20	2.5	0.05
40	5	0.1
60	7	0.7
80	12	1.2
100	22	3.1

Fig. 8 shows the simulation results with the humidity variation.

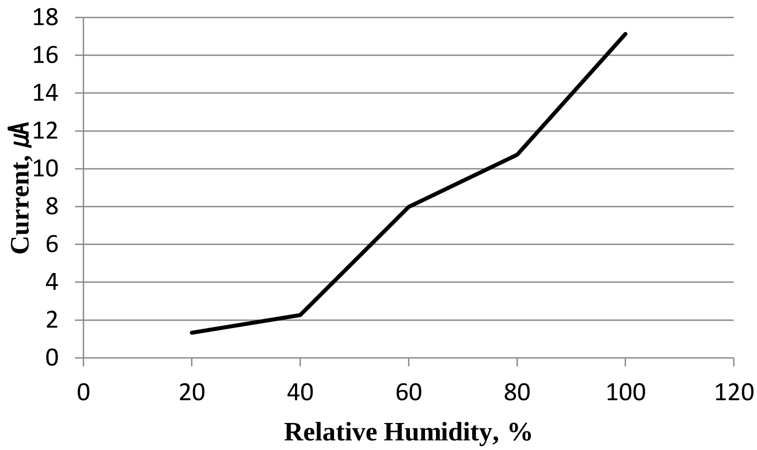

Figure 8.Current-Voltage characteristics for the humidity variation (NO_2 gas concentration 20 ppm, bias voltage=0.9V)

In the simulation, we use the conductivity for 1M H_2SO_4, 2M KOH, and 2M KCl as the pretreatment solvent based on the previous work [40]. The values are shown Table 2.

Table 2. Proton conductivity of Nafion membrane to the kinds and concentration of electrolyte

Pretreatment solution	Concentration	Conductivity (S/m)
H_2SO_4	1M	2
KOH	2M	0.4
KCl	3M	0.25

As shown Fig. 9, when we used 1M H_2SO_4 as a pretreatment solvent, the sensor presents the high state in terms of not only current intensity but also sensitivity than the other cases for NO_2 gas, 1-20ppm level.

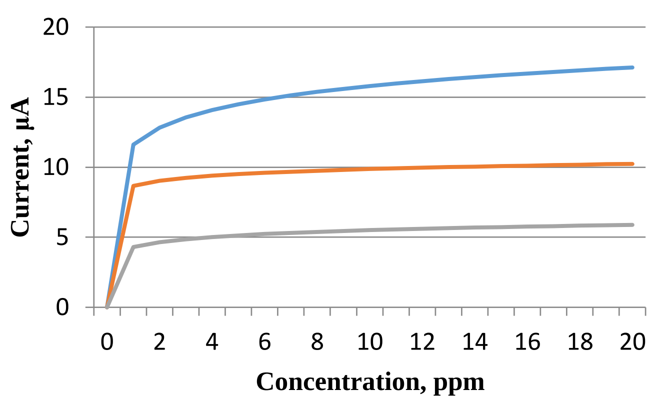

Figure. 9. The current characteristics of three sensors with different pretreatment solvent versus NO_2 gas concentration.

2.2. Experiment plan

From the simulation results, experiment plan draft is written for NO_2 gas sensor manufacturing and completed under the assistance of an advisor as following items.

- Preparing ceramic substrate
- Cleaning substrate (ultrasonic cleaning, distilled water cleaning)
- Substrate drying
- Printing of electrode pattern using conductive silver ink

(screen printing)
- Drying
- Printing of Nafion film (screen printing)
- Sintering
- Packaging

3. Investigation and result discussion

3.1. Investigation

For the practical requirements to enhance creativity of student and student directed teaching, all members of 2 experiment groups are encouraged to answer questions. Each answer is according to score from 1 to 10 for all questions. There are 5 following questions.

- Have you learned new knowledge during course?
- Have you solved problems arising from course?
- Have you improved your practical ability?
- Have you learned working skill?
- Do you understand all problems in the lecture?

Especially, 5th item is prepared to investigate effect of reduced time of lecture for basic theory on cognition rate of student due to combination of simulation software. Investigation result is listed in table 3.

Furthermore, averaged final grade of students who graduated typical course for last 3 years is compared with final grade of students who graduated improved course. The final grade reflects cognition of student about basic theory, designing skill, collaborating ability and manufacturing skill. For knowledge investigation concerning with manufacturing skill designing, verifying through simulation and optimizing are conducted. It is important to collaborate activities of groups for complex planning and implementing. This collaborate activity is arising as a crucial factor nowadays. Thus collaborate ability is contained to testing items. Assessment to collaborate ability is based on solve state and time of putted assignment on each group. Comparison of final grade is shown in Table 3.

Table 3. Investigation item of student

Questionnaire	Rate
Have you learned new knowledge during course?	10
Have you solved problems arising from course?	8
Have you improved your practical ability?	8
Have you learned working skill?	10
Do you understand all problems in the lecture?	9

Table 4. Comparison of final grade

Item	Pass typical course	Pass improved course
Basic theory	9	9
Deigning ability	8	9
Manufacturing ability	8	9
Collaborating ability	8	10

3.2. Result and discussion

As table 3 shown, the answer to question “Have you learned new knowledge during course?” is positively rated as 10. This shows that boredom of some student passed lecture concerned typical course is eliminated and active attitude on printed electronics subject is also improved. The answer to “Have you solved problems arising from course?” is rated as 8 which is medium attitude. This rate is similar (rather low) with that of typical course and which is because of the fact that printed electronics course contains many problems of future work rather than solving methods like other subject. Which is because of further problems arising while studying on simulation tool. Furthermore, the answer to “Have you improved your practical ability?” is rated positively as medium of 8. Which is improved rapidly rather than “low” attitude of student passed typical course and makes a great point of verifying practicality of the course. Because of daily arising practical requirement on manufacturing method based on printing, the answer to “Have you learned working skill?” is rated most positively as 10 which is improved than typical course. The answer to “Do you understand all problems in the lecture?” is rated medium of 9 which is a little greater than typical course. It is demonstrated that introduction of simulation tool to the course is positively impacted not negatively, on basic theory in the condition of reduced period of teaching basic theory due to further teaching simulation tools. It is related with the fact that student cognate more deeply about certain electronic device in the accordance with finding using method of simulation tool, modeling and simulating. Though all devices described in the course are not necessary to model and simulate, by limiting simulation tool on typical and designing complex gas student learned knowledge about sensor field in high level. As table 4 shown there are several successes of improved course. It is expected that there will be positive effect of introducing simulation on printed electronics course. Final Grade of basic theory is equal to 9 which is a verification of student attitude according to above questionnaire of "Do you understand all problems in the lecture?". Also in the terms of designing ability and manufacturing ability, the grade is equal to 9 which is superior than typical course of grade 8. As the answer to "Have you improved your practical ability?" indicates, there are some improvement in experiment practice by introducing simulation tool. The final grade of collaborate ability is remarkable which is radical development due to improve course (collaborate item of table 4). The improvement of collaborate ability is because of the fact that student realized proactivity and future effect of the printed electronics course, also attended the lecture and practice actively, also actively simulated, designed and discussed in group study.

4. Conclusion

For the current state of developing printed electronics as an independence major field, COMSOL Multiphysics is introduced to printed electronics course to depress some defects (described in section of introduction) which is occurred in teaching printed electronics to Microelectronics student. By investigating and comparing about typical course and newly improved course, there are following results.

- There is similarity in final grade of basic theory between typical and improved course. It shows that student can acquire basic theories about printed electronics in the condition of reduced learning period of basic theory because of introducing simulation tool to the course.
- Designing and manufacturing ability are improved, which reveals proactivity of improved course
- Collaborating ability also is improved, which is concerned with organizing and focusing on group activities more times than typical course.

In conclusion, improved printed electronics course depressed many defect which occurred during developing printed electronics as an independence field and this style of curse will be effective to enhance theoretical learning, practical ability and collaborating ability of under-graduating student.

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