行政院國家科學委員會專題研究計畫　期中進度報告

新型高效率微致動器及其應用在微機電與微光機電系統之研究(2/3)

計畫類別：個別型計畫
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計畫主持人：徐文祥

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報告類型：精簡報告
報告附件：國際合作計畫研究心得報告
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中　華　民　國 95 年 1 月 29 日

行政院國家科學委員會補助專題研究計畫
□成果報告 ■期中進度報告

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成果報告類型(依經費核定清單規定繳交)：■精簡報告 □完整報告

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
□出席國際學術會議心得報告及發表之論文各一份
■國際合作研究計畫國外研究報告書一份

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□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

執行單位：國立交通大學機械系

中華民國 95 年 1 月 16 日

一、中文摘要

本計畫提出一串聯式雙層板微熱致動器，其原理是串接數個基本微熱致動器，累積其位移而產生垂直方向之大位移量。每個基本微熱致動器包含兩種雙層板結構及一個拘束樑。與同尺寸下之傳統雙層板微熱致動器相比，此設計可提供較大位移，製作上是利用面型加工技術製作，材料主要由鋁及多晶矽構成。在此用4個基本單元來驗証設計概念，面積約510 x 400 μm^2。由實驗發現在4.5V時，可提供約22.5 μm垂直位移。操作溫度並經由熱像儀量測，4.5V時約為147℃，10V時仍低於400℃，與ANSYS電腦膜擬結果相當接近。

英文摘要

Here a cascaded bimorph actuator is proposed by integrating several novel actuation units to accumulate the vertical displacements. Each actuation unit comprises two types of bimorph beams and a constraint bar, and both beams will stretch outward with respect to the constraint bar while heating. In comparison with other three conventional bimorph actuator designs at the same device size, it is shown that the proposed design can provide larger vertical displacement. The proposed cascaded bimorph actuator is fabricated by surface micromachining technique and released by XeF_2 silicon isotropic etching. Whole suspended structure consisting of the polysilicon and the aluminum is around 510 x 400 μm^2 with four actuation units. The resistance is about 650 Ω. In testing, the fabricated device is shown to provide reversible vertical displacement of 22.5 μm at 4.5 V, and the operating temperature is measured by an infrared thermal microscope (InfraScope II, QFI). The calibrated maximum temperatures are compared with simulated results by ANSYS 6.0 in good agreement. It is found that the maximum temperature is 147 °C when the input voltage is 4.5 dc volts, and the maximum temperature is below 400°C even at 10 V.

Keywords: thermal, bimorph, cascaded, actuator, heating region

二、計劃緣由與目的

A micro actuator with larger output force and displacement at a compact size is always the research goal in MEMS area. A single micro actuator usually can provide only limited output force and displacement. Therefore, proper integration of several basic actuators into an arrayed structure becomes an attractive way to magnify the output. In electro-thermal microactuators, thermal bimorph effects have been applied widely to microactuators for large deflections and moderate forces under IC-level low driving voltages. One typical structure type used in thermal bimorph actuation is the cantilever structure. Thermal bimorph structures with beam and membrane types are also found in many applications .

However, in thermal bimorph actuators, larger displacement usually requires longer beam length, which will occupy larger device size and may be limited by the releasing method in fabrication process. In order to further magnify the displacement in a compact size, here a cascaded electro-thermal bimorph micro actuator is proposed. Comparing to conventional bimorph actuators, the proposed micro drives are expected to provide larger displacement at the same device size. Silicon-based surface micromachining technique will be used to fabricate the device, and the thermal and mechanical behaviors of the device will be investigated experimentally and analytically.

三、研究方法

PRINCIPLE AND CONCEPT DESIGN

Figure 1(a) illustrates three conventional bimorph structures with different heating regions, full bimorph type, bimorph in central region type, and bimorph in edge region type, respectively. From our previous studies, when the upper layer has larger coefficient of thermal expansion (CTE) and two ends of the bottom layer are fixed, the full type and central region type will provide upward deflection while heating. The edge region type will generate downward deflection on the other hand.

The proposed cascaded bimorph actuator (CBA) is formed by connecting several basic actuation units in serial. Each actuation unit comprises two bimorph structures and a constraint bar. Two bimorph structures which are edge region type and central region type to generate downward and upward deflections, respectively, are arranged in transverse way. Connecting these two different bimorph beams and a constraint bar longitudinally can form the basic actuation unit. While heating, the constraint bar will limit the transverse thermal expansions of bimorph beams, then both beams will stretch upward or downward with respect to the constraint bar. Since the vertical displacement of bimorph beams depends on transverse length, not the longitudinal length, when several actuation units are connected in serial to form a cascaded structure, as shown in Fig. 1(b), the outward displacements from each actuation unit can be accumulated to provide a larger vertical displacement with a smaller longitudinal size.

Figure 1 (b) illustrates the design of two actuation units with two extra central-type bimorph beams, the definitions of geometrical parameters are also shown. The upper layer, denoted as 1st layer, has larger CTE than the bottom heating layer denoted as 2nd layer. The length and width of the beam are denoted by Lw and W, respectively. The longitudinal length of the cascaded bimorph actuator is denoted by 2L. The symbols ER and CR represent the length ratios of bimorph parts to the whole length of edge region type and central region type, respectively.

SIMULATIONS

Here finite element software ANSYS® 6.0 is used to investigate the thermal and mechanical behaviors of the proposed device. In order to realize the advantage of the proposed design, deflections of three conventional designs with different heating regions of bimorph beams in Fig. 1(a) are first used to compare with the proposed CBA through simulations under different elevated temperature. As shown in Fig. 2 , with the same dimension and materials, the full type and the central region type will generate upward displacement. The edge region type will exhibit downward displacement, and the proposed CBA in Fig. 1(b) can provide the largest vertical displacement owing to the accumulations from each actuation unit. Also, the deflection of full type is larger than that of central heating region type.

For further investigation, CBA consisting of four actuation units and two extra bimorph beams is used, temperature distribution is also investigated. Since the proposed micro actuator is complicated, and the constraint bars in the proposed micro actuator may consume thermal energy through heat conduction and affect not only heat transfer but also output displacement. To analyze this complicated structure, sequentially coupled analysis technique is used in simulation, including two steps. The first step is the nonlinear electro-thermal analysis with 3-D 69-solid element, and the second step is the nonlinear thermal stress analysis with 3-D 45-solid element. Since the device is symmetric, the finite element model is built in half for computational efficiency. The modeling is fully surrounded by air and the mesa of silicon substrate, which is built beneath the electrical contact pad. Aluminum and polysilicon are selected respectively as the upper and bottom layers of CBA, respectively due to the large difference in CTE and our fabrication capability. Also, thin thermal dioxide is used as the isolation of electro-thermal layer when the polysilicon also acts as the electrical heating layer. Table 1 lists the material properties used in simulation.

In electro-thermal analysis, reference temperature is set at 25°C on surface of silicon substrate and the ambient air. Electric potential loads are applied on the top surface of the contact pad and on the symmetrical plane of the connecting bar. Both conduction and convection of heat transfer are considered in analysis. Therefore, the thermal conductivity and specific heat of the structure materials and air are considered. In addition, the reflow of aluminum layer will occur when the temperature is higher than 400°C, therefore the cases with maximum operating temperature of CBA below 350°C are simulated. Figure 3 shows the effect of air gap between the suspended structure and the silicon substrate is investigated first. It is found that the output displacement and the maximum temperature will increase with the air gap owing to the tougher thermal conduction through thicker air gap. Figure 4 shows the output displacement under different thickness ratios between Al layer and polysilicon layer, where the polysilicon and thermal dioxide are set as 1.5μm and 0.2μm, respectively. Thickness ratio of 0.8 provides the largest displacement. The output displacement under different bimorph length ratios ER and CR for outer region and central region types, respectively, are shown in Fig. 5. The optimal length ratios for central and edge types are all 0.5. The width ratio between the constraint bar and the bimorph beam, D/W, is also investigated. In thermal simulation, as shown in 6, higher temperature can be induced at smaller D/W, because of less heat dissipation through a narrower constraint bar. In general, higher temperature at bimorph beams, i.e. smaller D/W, will generate larger vertical displacement with fixed ends, as shown in Fig. 6, output displacement decreases from D/W=2.0 to 6.0. However, a narrow constraint bar will thermally expand more easily due to high temperature, which will seriously damage the boundary condition of bimorph beams to cause vertical output displacement decreasing, that is what happens in Fig. 6 for D/W= 0.5 and 1.0. Therefore the optimal D/W ratio can be found as 2.0, where largest displacement is achieved without reaching highest maximum temperature.

FABRICATION PROCESS

In this work, the cascaded bimorph actuator is fabricated by surface micromachining and released by vapor phase etching with xenon diflouride, XeF_2 (X3 Series in Xetch®). Furthermore, the proposed actuator is consisted of the aluminum and the polysilicon as two major layers. The thermal oxide and the AZ4620® thick photoresist are used to cover and protect the whole device during the silicon isotropic etching. Plasma-enhanced chemical vapor deposition (PECVD) oxide is used here to be an isolated layer for the isolated electricity between the aluminum and the polysilicon layer. This three-mask process is illustrated in Fig. 7.

TESTING

For temperature measurement, Infrared thermal microscope (InfraScope II, QFI) is used here to measure the temperature image of CBA while heating. It provides automated spatial emissive compensation that produces a true temperature of the tested device. The focusing stage is controlled by the computer. The temperature resolution is 0.1°C at 80°C, and the calibrated range is from 30°C to 400°C. Also, the pixel resolution of temperature image is 6 μm at optics percentage of 5X. The fabricated sample is tested on a stage with controlled reference temperature of 70°C. Then two probes, connecting from power supply, are contacted with CBA under different input voltages. Figure 9 shows the measured temperature image at 5 Volts. The locations with the highest temperature can found to be around the middle point and the bimorph structures near the middle two actuation units.

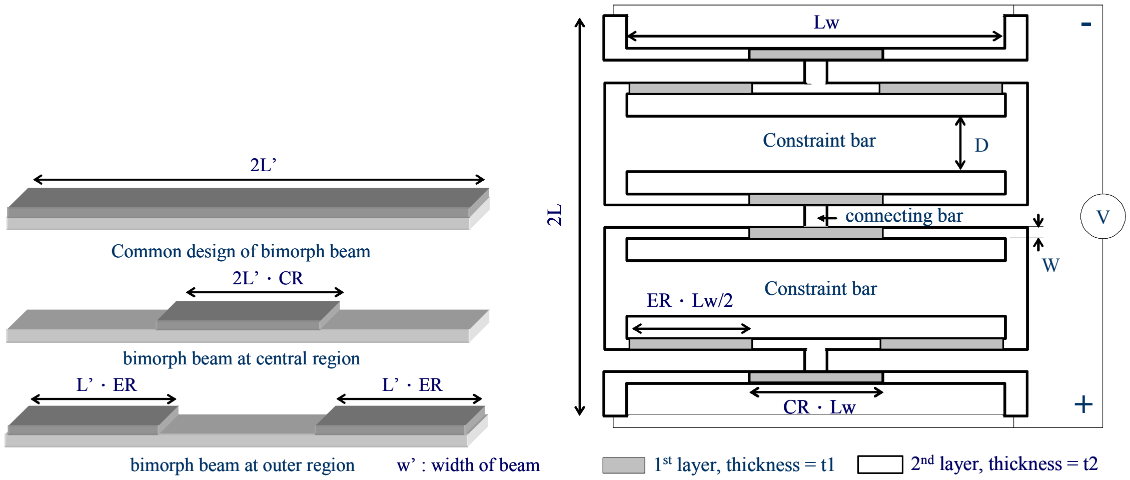
The comparison between simulated and calibrated maximum temperature at different input voltages is shown in Fig. 10 with good agreement. It is found that the maximum temperature is 147 °C when the input voltage is 4.5 dc volts, and the maximum temperature is still below 400°C even at 10 V.

Displacement test is performed at the stage of the optical microscope, and the deflection is measured by recording the focal length difference when it is focalized on top surface of CBA at different voltages. In experiments, an irreversible deflection of CBA is occurred at applied voltage over 4.7 volts. Figure 11 shows the upward deflection of CBA with four actuation units at 4.5 volts. The measuring points of bimorph beams with central heating region, denoted A and E, have a displacement of around 9.5 μm, and the relative displacement from point B to point A, or point D to point E, is only about 6.5 μm. The maximum displacement happening at point C is about 22.5 μm, which is smaller than we expected. Figure 12 shows the simulated and measured vertical displacement at different input voltages. The mismatch may come from the initial curvature or so-called geometrical imperfection owing to the residual stress in fabricating the bimorph structure. The curved shape of bimorph beam would cause unstable deflecting behavior while heating. In our simulation, the bimorph structure is assumed flat, no initial curvature is considered. Thus, the output displacement of the bimorph structure may deviate from simulation, even with the accurate temperature distribution model.

四、結論

A cascaded bimorph actuator is designed, fabricated, and tested here. The fabricated device is shown to provide reversible vertical displacement of 22.5 μm at 4.5 V, and the calibrated maximum temperatures are compared with simulated results in good agreement. It is found that the maximum temperature is 147 °C when the input voltage is 4.5 dc volts, and the maximum temperature is below 400°C even at 10 V. However, it is found that the measured vertical displacements deviate from the simulation evidently, which may be caused by the curved shape of the bimorph beam. Further investigations on other low-temperature fabrication technique or structure materials may be helpful in future improvement.

五、圖表



(a) (b)

Fig. 1 Illustration of the concept design and the geometrical parameter definitions. (a) Bimorph beams with three types of different heating region. (b) Minimum component with two actuation units and two extra bimorph beams.

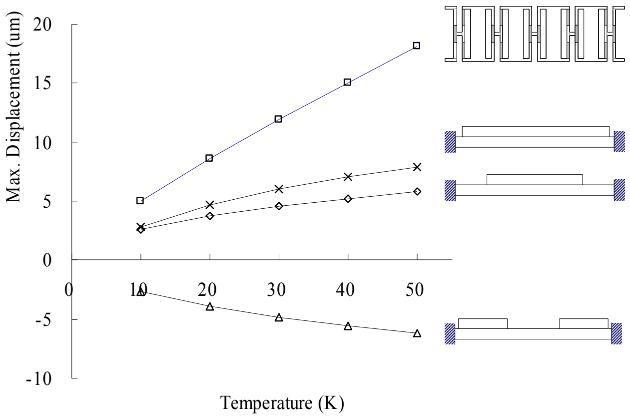


Fig. 2 Simulations with four types of designs under different elevated temperatures. (t1= t2=1.0µm, 2L'=2L=510 µm, Lw = 400 µm, ER=CR=0.5)

Table 1. Material properties for the simulation model

Material	Al	PECVD SiO_2	LPCVD PolySi	SC-Si	Air
Young's modulus (GPa)	69	57	150	162	-
Density(kg/m^3)	2692	2660	2330	2420	*1.293~0.456
Poisson's ratio	0.36	0.245	0.28	0.28	-
Resistivity (Ω-cm)	25e-9	-	9e-6	-	-
Conductivity (W/m*K)	237	1.1~ 2.09	34.0	*146.4~41.8	*0.024~0.056
Specific heat (J/Kg*K)	898.7	176~ 223	754	706.4	*1006~1093
CTE (10^{-6}/K)	27.95	0.4	2.33	*2.56~4.10	-

* Temperature dependent - Not used in simulation

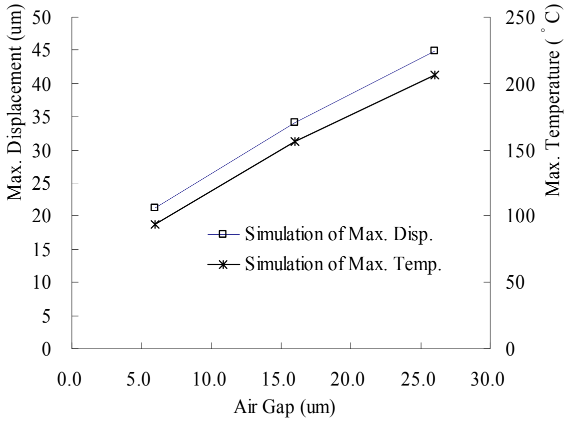


Fig. 3 Effect of air gap

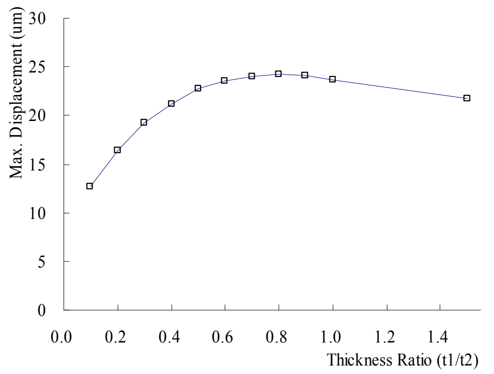


Fig. 4 Effect of thickness ratio of bimorph beam

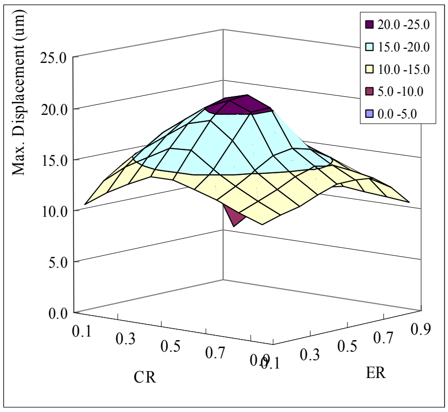


Fig. 5 Effects of length ratios, CR and ER

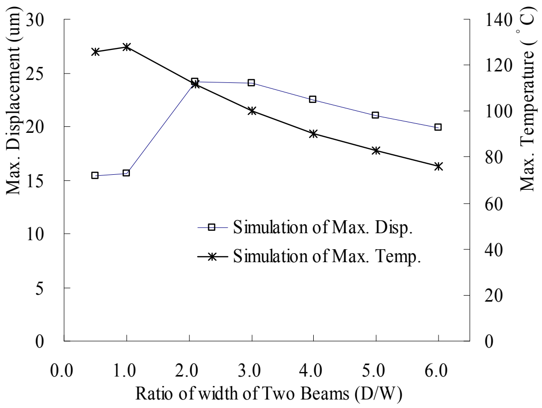


Figure 6 Effect of width ratio, D/W

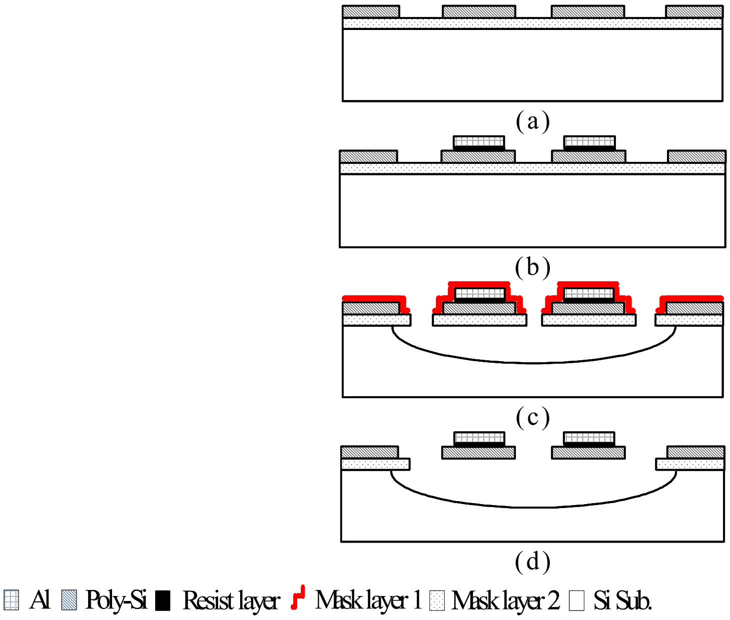


Figure 7 Illustration of the fabrication process using surface micromachining and XeF_2 isotropic silicon etching.

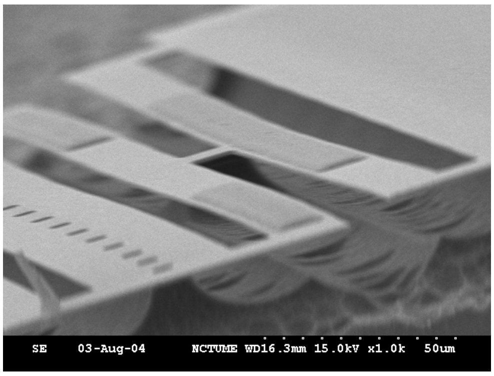


Fig. 8 SEM of the fabricated cascaded bimorph actuato

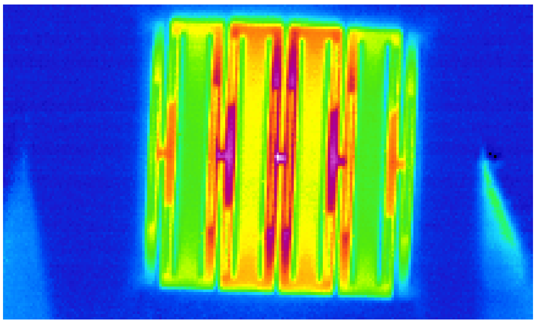


Figure 9 Measured temperature image at 5 V.

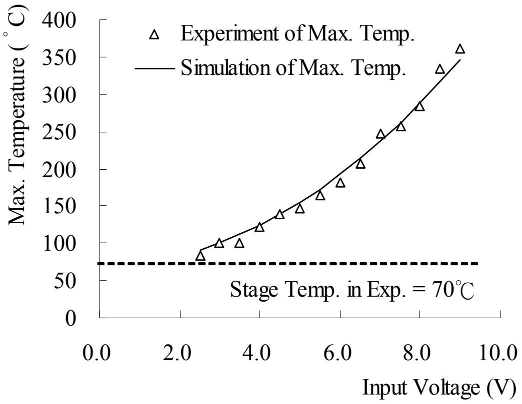


Figure 10 Calibrated and simulated (by Ansys 6.0) maximum temperature of the cascaded bimorph actuator with four actuation units under different input voltages

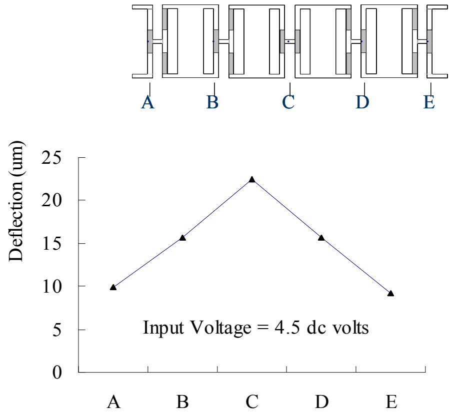


Figure 11 Calibrated displacements of different locations at 4.5 V.

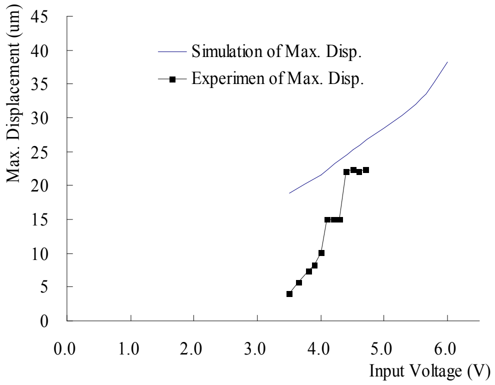


Figure 12 Comparison of simulated and measured output displacements under different input voltages

參加 ASME IMECE 2005 暨 赴加拿大整合製造科技所出國研究報告

時間：2005 年 11 月 5 日至 11 月 15 日
地點：美國奧蘭多市及加拿大 整合製造科技所
USA Orlando &Canada NRC IMTI
(Integrated Manufacturing Technology Institute)
報告人：交通大學機械系 徐文祥 教授
NSC 94-2212-E009-005

一、前言

IMTI(Integrated Manufacturing Technology Institute) 是加拿大NRC(National Research Council)下的研究單位，本人2001年9月曾與我國國科會團隊赴加拿大IMTI參加NSC-NRC Advanced Manufacture Technology Workshop，與IMTI有了初步交流，而後獲國科會核准，開始執行此一國際合作計劃，.第一期執行時間為92年8月1日至93年3月31日，本期為第二期，時間為93年4月1日至94年3月31日，合作對象是加拿大國家研究委員會(NRC)所屬整合製造科技所的精密雷射微加工組，以本實驗室所提出的可提供大輸出位移的新型大伸展式微致動器結構為合作研究重點，結合交通大學及加拿大整合製造科技所在不同微製造技術的專長，建構數種微致動器，並希望進一步應用在微光機電系統的光學元件，搭配進行設計與製造技術的開發。第一期重點在水平式微熱致動器的開發，第二期在垂直式微熱致動器的開發，我方是微致動器的結構設計分析與以黃光半導體微影製程製作，而IMTI則是以雷射加工技術製作為重點。第一期的研究成果已發表兩篇期刊論文，而第二期部份成果也在2005年11月之ASME IMECE此會議中發表，故此次行程安排即配合此活動，先至美國論文發表，再轉去加拿大進行研究進度討論。

二、經過

美國機械工程師學會(ASME)每年舉辦的國際機械工程研討與展示會(IMECE)是機械領域裡面的一場盛會，除了世界各地的專家學者參與之外，還有相關廠商出席參展，是一個可以接觸到學術界以及產業界的會議。2005 年 11 月 6-10 日是在美國佛羅里達州奧蘭多市的天鵝及海豚旅館裡舉辦，有超過 600 sessions，涵蓋將近 50 個領域在這個會議中進行討論，發表超過 2600 篇的論文，可以說非常的盛大。

另外，還有 14 場的餐會，可以跟相關領域的學者一起用餐，提供互相認識的機會。

本實驗室共發表兩篇論文，並有我一位博士生共同參加，題目分別是在可撓式高分子基板上以 EWOD 驅動力驅動液珠 3D 移動的研究，及串聯式雙層板熱致動器設計與製造，報告的時間各被安排在禮拜三的早晨及下午，上午那場參與的人數較少，但是大家討論的氣氛相當熱絡，不單單是在會議的進行中提出問題，會後也有相當多的私下討論。有幾位教授對我們的論文表示興趣，在高分子材料的應用上，及流體驅動相關問題，透過意見的交換給我們得到相當多的啟發，對於未來的發展也更有信心。

禮拜三下午發表的論文，也有不少參與者表示興趣，還遇見高雄應用科大的許光城老師，以及幾位台灣來的學者，大家熱絡地互相交換意見。有意思的是我們發表的其中一篇是被安排在「整合及封裝奈微米電子系統」領域中，與一開始投稿時所投的「微機電系統」有點不同。在仔細研究主辦單位安排的議程後，可以看出，微機電相關的論文不一定會安排在微機電系統領域中，而是依照研究的主題，分散在各個不同的領域。這表示現在微機電，已經廣泛的使用在其他領域中，使得微機電技術變成一個工具，進而協助各領域的深入發展。

11月10日我即轉去加拿大中南部London市郊區，與美國底特律相距約1個半小時車程，距多倫多市反而有約3小時車程，所以London市中許多工業與汽車零組件製造有關，完成後再運往底特律組裝。而我這次前往IMTI就是由美國底特律入境再轉往IMTI所在的London市。住宿方面，由於IMTI旁就有一精緻旅社，走路至IMTI約5分鐘即可，十分方便。

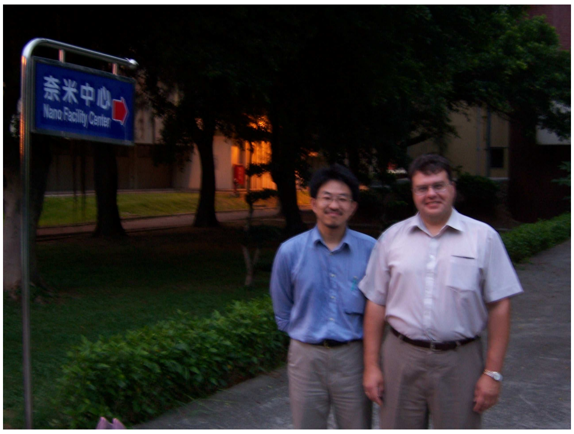
此次交流主要包含兩個部分，一個是了解雙方進度，討論一些設計及量測上的問題，第二部分是對計畫未來走向的交換意見。與我合作進行此一計畫的加拿大IMTI單位是精密雷射微加工組，負責人是Dr. Nikumb，主要執行負責的研究員是Dr. Bordachev，並有多位工程師協助製程及量測。其中Dr. Bordachevy在2005年6月中旬有到台灣參加國科會舉辦之中加交流會議，並到新竹交大訪問，除了針對本計畫之進度及內容進行討論外，我還安排Dr. Bordachevy參觀交大、同步幅射研究中心及園區新磊公司，讓他對國內產學研環境印象深刻。

由於本計畫欲研發的大行程伸展式微致動器設計主要是由本實驗室提出，一開始我方是由半導體黃光微影製程所製作，在尺寸設計上皆是以此製程能力為設計基礎，而IMTI具有強大的雷射微加工能力，可加工更多樣性之微致動器材料，但與半導體式微加工製程相比，其尺寸精度較差，所以在設計上必須放寬關鍵尺寸的要求，而對他們此小組而言，以前都是以雷射微加工技術製作微結構，本計畫是他們第

一次製作微致動器，他們十分重視，經過第一期的合作，他們也建立了良好組裝及量測設備，我方以金屬式面型微加工技術製作之成果已為J.MEMS期刊接受，而IMTI以雷射微加工技術完成之成果也已為J.IMSS期刊接受，此次除討論第一期所發展之LSMD未來應用發展方向外，也對第二期所研發之CBA微致動器在用雷射微加工上的多項課題交換意見。一方面我報告了我方目前製作及量測結果上的進展，也現場了解加拿大這邊的進展及其製作與量測過程，並針對我方設計上的一些課題進行討論，包含未來可以在尺寸、材料及輸出力量測上的後續研究重點。

三、心得

此次感謝國科會補助，讓我有機會進行國際交流計畫，尤其合作對象是研究單位，而非單純學校教授，深感其支援人力充足，例如其驅動電路及量測裝置皆是由專職研究人員進行設計製作，在品質及效率上皆十分良好，而此次透過當面交流，雙方都覺得獲益量多，對增進了解及計畫持續推動有直接助益。



圖一 Dr. Bordachevy 參觀交大

圖二 Dr. Bordachevy 參觀新磊

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圖三 本實驗室博士生在IMECE發表論文 圖四 在加拿大IMTI講演