AD-A251 617

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

2. REPORT DATE: June 1, 1992

3. REPORT TYPE AND DATES COVERED: Final Technical Report

4. TITLE AND SUBTITLE

Multilayer Actuator Products in Japan

5. FUNDING NUMBERS

N00014-92-J-1059 (Grant)

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The Pennsylvania State University
Materials Research Laboratory

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Department of the Navy
Office of the Chief of Naval Research
800 North Quincy Street CODE 1513: MBL
Arlington, VA 22217-5000

10. SPONSORING MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

N/A

12a. DISTRIBUTION AVAILABILITY STATEMENT

Distribution unlimited

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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Multilayer actuators can be divided largely into two categories: one is a stack type, in which sintered disks are stacked with an alternate electrode in between each ceramic disk, and the other is a cofired type. There are various structures within the cofired multilayer actuators: A) ceramic multilayer capacitor (MLC) type, B) plate-through with application of insulator at alternate electrodes, and C) slits or gaps with MLC structure type. Each type has its own advantages and disadvantages, which are summarized in this report.

A new structure actuator which does not belong to above categories, a three-dimensional interdigital electrode structure (3D-IDE), is being developed at Tokin Research Lab. The number of fine electrode lines controls the multiplication of piezoelectric effect, and multilayering is performed perpendicular to the displacement direction. Preliminary test results indicate that the 3D-IDE provides improved reliability compared with commercial plate-through type multilayer actuators.

14. SUBJECT TERMS

Multilayer actuators, PZT, Internal electrode configulation

15. NUMBER OF PAGES: 21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

NSN 7540-01-280-5500

FINAL TECHNICAL REPORT

"MULTILAYER ACTUATOR PRODUCTS IN JAPAN"

Department of the Navy

Office of the Chief of Naval Research

Grant No: N00014-92-J-1059

P.I.: Shoko Yoshikawa

Materials Research Laboratory

The Pennsylvania State University

SUMMARY

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A new structure actuator which does not belong to above categories, a three-dimensional interdigital electrode structure (3D-IDE), is being developed at Tokin Research Lab. The number of fine electrode lines controls the multiplication of piezoelectric effect, and multilayering is performed perpendicular to the displacement direction. Preliminary test results indicate that the 3D-IDE provides improved reliability compared with commercial plate-through type multilayer actuators.

1. INTRODUCTION

Interest in piezoelectric or electrostrictive ceramic actuators is increasing rapidly as research in the area of "smart materials" and "adaptive active control" evolves. The ceramic actuators have definite advantages over the conventional electromagnetic actuators because of their lower power consumption, reduced heat generation, and smaller sizes. One disadvantage of ceramic actuators in some applications is their small displacement value. For this reason, two kinds of piezoelectric actuators are in practical use. One is a bimorph element using a bending motion, and the other is a multilayer element using internal electrodes. For the applications which require large force and precise control while maintaining a reasonable displacement, multilayer actuators are necessary.

The P.I. has spent six months working on multilayer actuators, focusing on their structures and reliability, working in the R&D lab of one of the major manufacturers of multilayer actuators. Because of time limitations, the ceramic material used in this study was limited to soft PZT ($0.5Pb(Ni_{1/3}Nb_{2/3})O_3$-$0.35PbTiO_3$-$0.15PbZrO_3$), which was originally developed at NEC, and is now produced at Tokin Corp. as NEPEC-10. Electrostrictive ceramic materials such as lead magnesium niobate doped with lead titanate (PMN-PT) are not yet commonly used for actuators in Japan, mainly because of their limited temperature range. One disadvantage of applications of PZT for "smart material" is the large D-E hysteresis, which makes it difficult to use as both sensor and actuator. Recent studies in Japan, however, are showing that with appropriate circuitry to compensate for hysteresis, PZT can be used as both sensor and an actuator.[1] The author was also involved in the development of a new type of actuator at Tokin Corp., and with the reliability tests performed on the new actuators as well as those on commercialized multilayer actuators.

The history and current status of multilayer actuator development is summarized in the next section, including advantages and disadvantages of each multilayer actuator followed by a description of the new actuator design. Detailed information regarding this actuator is presented in a separate paper.[2] Multilayer actuator reliability issues are discussed without compromising the company's confidential information.

2. HISTORY AND CURRENT STATUS OF MULTILAYER ACTUATORS IN JAPAN

2.1. Stacked Actuators

When the need to multiply the piezoelectric ceramic's strain in the thickness direction arose, the first multilayer was made by stacking the number of piezoelectric ceramic plates bonded together with an adhesive or with spring loaded structure. Representative actuators are NTK's Piezostacks [3,4] shown in Figure 1 and Nippon Denso's piezoelectric actuators. The adhesion between electrode and ceramic tends to be weaker so that relatively large pre-stress is required. This pre-stress has an important role in not only preventing the separation between electrode and ceramic, but also the breakdown of ceramic itself when a large pulse is applied. Thus, most of the multilayer actuators are fabricated in a prestressed condition, or require users to apply constant stress during its use. The stress, of course, must be within the range of the individual actuator's generative force.

The electrode structure is so called plate-through, which utilizes all of the piezoelectric plate thickness direction and eliminates the inactive areas as observed in multilayer ceramic capacitor type electrode, thus providing the maximum displacement possible. The electrode materials are made of thin conductive foil, and each piezoelectric ceramic surface has to be polished and electroded prior to the stacking. Ohnishi and Morohashi showed that thin (10μm) silver foil could be bonded between ceramic plates by the application of pressure and heat (up to 900°C) to produce low cost stack type actuators.(5)

The advantage of the stack actuator lies in the possibility of producing defect-free, well-sintered ceramics without electrode ink diffusion, thus eliminating short circuiting of electrodes. The disadvantage is, however, that it requires a relatively high driving voltage, because it is difficult to manufacture thin ceramic plates. It is also undesirable for miniaturization and mass production.

In order to overcome these problems, the technology of producing multilayer ceramic capacitors was investigated leading to the manufacture of co-fired ceramic multilayer actuators.

2.2 Co-fired Multilayer Actuators

The first concern in producing co-fireable piezoelectric ceramic actuators was ceramic-electrode interactions. Most PZT compositions require higher sintering temperature, and if co-fired with Ag/Pd electrode in multilayer actuators, react with silver to modify its properties. For this and other reasons, Pt ink is still in use, since the use of Pt allows ceramic sintering to be carried out at higher temperatures thereby obtaining proper densification of PZT. However, as with multilayer capacitors, it is important to use less expensive electrode inks such a Ag/Pd (70/30) or pure Ag to reduce the cost of the actuators. Most of the PZT multilayer actuators produced currently in Japan utilize Ag/Pd internal electrodes by reducing the PZT sintering temperature with additives. Tokin's NEPEC-10, for example, can be fired at 1090°C, although their actuators go through HIP processing afterward for further densification. Another concern is the adhesion and diffusion properties between the electrode and ceramics. Various special techniques in each company, such as adding a small amount of fine ceramic powder with the same composition as the ceramic layer to the ink paste, have been developed.

Several structures for co-fired multilayer actuators have been designed as discussed in the following sections.

A. Multilayer Ceramic Capacitor Electrode Structure

Multilayer capacitor (MLC) technology has been established for quite some time, and efforts to produce thinner layers in miniature MLCs is continuing. The original idea to utilize this technology for multilayer actuators was put forward in a paper by Bowen et al. [(6)] at the Penn State University Materials Research Laboratory. This structure, however, has not been commercialized because of the piezoelectrically inactive areas indicated in Figure 2 (area a). These inactive regions not only restrain displacement, but also lead to large internal stress concentration and fracture.

B. Plate-Through Electrode Structure

NEC subsequently developed the plate-through electrode configuration shown in Figure 2 (B) with glass insulators positioned on alternate sides of the internal electrodes. This multilayer actuator has been commercialized with various types of packaging, and production was transferred to the Tokin Corporation several years ago.

This structure overcame the problems observed with the MLC electrode structure and provides maximum displacement. The problems, however, are: (i) it is difficult to achieve very thin separation distances because of technical limitations in the formation of fine insulator lines, (ii) excepting the two sides of the actuator element to which glass insulator was applied, the internal electrodes are exposed, since application of glass insulator is performed to a larger block of actuator and sliced to the sample size. For these reasons, it is difficult to produce ultra-thin layers (thinner than 100 μm) for low driving voltages, and most of the actuators have to be hermetically sealed in a casing even after a polymer coating is applied to the actuators to avoid humidity which causes shorting at the exposed surfaces of the electrodes.

C. Slit or Internal Gap Electrode Structure

Although the plate-through actuators are in commercial use, NEC has proposed [8] a new structure with slits, as shown in Figure 2 (C). In this actuator, the internal stresses generated in the inactive areas of the MLC type, (Figure 2 (A) c) are relieved by slits, thus reducing the possibility of mechanical failure. Ultra-thin ceramic layers can be produced in this way, avoiding the problems stated in the previous section. Carbon paste is applied in every nth internal electrode layer surrounding the area of internal electrode. The carbon is burned out along with other organic materials in the green body, leaving slits on the actuator element. Multilayer actuators with ceramic layer thicknesses of 25 μm have been made by this method, far smaller than the layer thicknesses of 110 μm of the commercialized plate-through actuators.

A similar structure has been produced by Mitsui Petrochemical Industry, using internal gaps, as shown in Figure 2 (D), instead of slits.[9]

Both structures provide improved reliability, particularly in a humid environment, because of the elimination of both glass insulator failures and exposed internal electrodes.

3. INTERDIGITAL ELECTRODE ACTUATORS

Interdigital electrodes (IDE) have been widely used in surface acoustic wave transducers.(10,11) Recently, Hirose and coworkers have analyzed piezoelectric ceramic bending vibrators with IDE (12), and the first application of IDE for actuators has been demonstrated with a torsional actuator developed at Tokin Corp.(13) The Murata Mfg. Co. has a patent (14) which uses IDE on both sides of piezoelectric ceramic board, and another patent followed which described a structure containing multilayered boards made by stacking green sheets and co-firing, as shown in Figure 3.(15)

At Tokin, a similar electrode configuration was applied to their actuator PZT material and displacements perpendicular to the electrode lines were observed. Utilization of transverse coupling coefficient k_{31} was also explored with the structure shown in Figure 4. This actuator produces a negative displacement with positive applied voltage. Because of the lower value of k_{31}, which is about a half of k_{33} for PZT, the absolute displacement of this actuator is not as large as that for the longitudinal effect. The study by Hirose (12) showed, however, k_{31} works more efficiently in the case of IDE, because the electric force lines underneath each electrode are perpendicular to the surface of the ceramic so that the small area under the electrode moves with transverse effect even when the longitudinal effect was used. Nevertheless, the larger value of k_{33} led to continued investigation of the longitudinal effect with IDE.

In order to achieve large displacement with relatively low driving voltage, numerous electrode lines with narrow gaps are required. Electrodes on the same surface of the ceramic with alternating polarity tend to short circuit more easily because of the inability to produce narrow electrode gaps by screen printing, and also the possibility of silver migration when the electrodes are exposed to air. Thus, Tokin has developed a structure in which the same polarity is applied to the electrode lines on one surface of the ceramic layer. Opposite polarity is applied to the next layer, whose electrode lines are shifted half a pitch. We have named this type of electrode arrangement "three-dimensional IDE" (3D-IDE). The structure, analysis, and properties of the actuators with 3D-IDE are summarized in the next three sections.

A. Structure

Figure 5 shows the structure of the actuators with typical dimensions used for the experimental samples. The ceramic layers were made of Tokin's NEPEC-10 as described in the Introduction, and the electrode material was Ag/Pd(70/30). The total number of electrode lines on one surface in this case was 106 and total number of active layer was 100 with an additional five dummy layers at the top and bottom of the stack. The electrode ink was screen printed on ceramic green sheets followed by stacking and pressing. Stacking is one of the critical processing steps, since mis-alignment reduces the longitudinal effect required for this design. The pressed stack was then cut into shape and fired after the binder burnout process was completed. External electrodes made from a glass containing Ag paste were applied to the two sides of the sample to connect the IDE and then fired. Lead wires were soldered onto each side.

As shown in Figure 6, the displacement direction of this type of actuator is perpendicular to the direction of stacking, unlike a conventional multilayer actuator, in which displacement occurs along the stacking direction.

Expected advantages of this structure are (1) easy amplification of the displacement by adding the electrode lines, whereas conventional multilayer actuators have some limitation on the number of layers, (2) longer life in humid environments by reducing exposure of the internal electrodes.

B. Analysis

Figure 7 shows the cross section of the fundamental unit of the actuator and the expected lines of electric force. The displacement in the structure shown in Figure 5 is a multiple of the unit displacement in the z-direction by the following number: n=2N-1 where N is the number of electrode lines. For the sample illustrated in Figure 5, n=106x2-1=211.

As shown in Figure 7, the electric field distribution in each unit area is nonuniform. Detailed theoretical analysis of the field distribution can be performed by a conformal mapping method or by a finite element method, which the author intends to perform in the future. For the time being, an approximate solution was obtained using the research carried out by Hirose (16). Figure 8 (A) shows his analysis for the case in which the electrodes are on the same side of the dielectric layer, while (B) illustrates our new structure actuator electrode arrangement. It is assumed that the direction of the residual dielectric polarization is the same as that for a dc-electric field in polarized state. Consider the coordinate system (x,y,z) at an arbitrary point on electric field line as in Figure 8 (B), where the z axis is in the direction of the electric field. Based on this coordinate system, one can obtain the materials constants for another coordinate system (x´, y´,z´). The constitutive equations for piezoelectricity are given by:

$$\begin{cases} [S'] = [s^{D'}]\,[T'] + [g']_t\,[D'] \\ [E'] = -[g']\,[T'] + [\beta^{T'}]\,[D'] \end{cases}$$

where symbols with (´) indicate quantities or constants in the coordinate system (x´,y´,z´); [S´] and [T´] are the matrices of a strain and stress, respectively; [E´] and [D´] are the matrices of an electric field and electrical displacement respectively; $[s^{D'}]$ is the compliance under the constant electrical displacement; $[g']$ is a piezoelectric constant; and suffix t indicates a transposition matrix. Letting the matrix of the dielectric constant be $[\varepsilon^{T'}]$, $[\beta^{T'}] = [\varepsilon^{T'}]^{-1}$ is given.

For the longitudinal mode, only T'_3 should be considered. The electric field E_3 tangential to the electric force lines is given by:

$$E_3 = -G(\theta)S'_3 + H(\theta)D_3$$

where $G(\theta) = (g_{31}\sin^2\theta + g_{33}\cos^2\theta)/s^D$
$H(\theta) = \beta^T_{33} + \{G(\theta)\}^2 s^D$

where $s^D = s^D_{11}\sin^4\theta + (2s^D_{13} + s^D_{44})\sin^2\theta\cos^2\theta + s^D_{33}\cos^4\theta)$

From this equation, $\theta=0$ and $\pm\pi/2$ gives $G(0)=g_{33}/s^D_{33}$ and $G(\pm\pi/2)=g_{31}/s^D_{11}$, thus it is better for θ to be small when optimizing the longitudinal mode. Small θ means smaller thicknesses of the piezoelectric ceramic. The study of the electrode width and pitch (a/p) ratio showed that smaller a/p ratio gave higher coupling coefficient k, although it is easy to see that k increases again when a/p is close to zero. Because of the limitations on fine line formation using screen printing, optimum experimental value for a/p ratio was 0.5 for the experimental layer thickness of 52 μm.

C. Properties

A plot of displacement with applied voltage for a typical sample is shown in Figure 9. Strain versus calculated electric field for the new design using three different electrode distances, e, f, and g, are shown in Figure 10 along with the corresponding data for a commercialized multilayer actuator (5x5x18mm) with conventional plate-through structure. These results indicate that the new structure with 3D-IDE is capable of producing large displacements by simply increasing the number of electrode lines. The actual field induced strain, however, is somewhat less than that of a conventional multilayer actuator because of the nonuniform field distribution for both poling and driving.

The capacitance of the new actuator depends on the electrode width, gap, and piezoelectric layer thickness. The configuration shown in Figure 5 gave a capacitance of 1400nF after poling.

Generative force of the sample measured with a strain gage was 350 kg/cm^2, and the value decreased as the number of electrode lines increased within the same sample length. Figure 11 shows the strain vs. generative force characteristics of two 3D-IDE actuators under electric drive.

The number and configuration of the internal electrodes changes the generative force as the mechanical properties vary. The ceramic NEPEC-10 elastic constant Y_{33}^{E} is 5.5×10^{10} N/m^2 (=5.6×10^5 kg/cm^2). The stress calculated from this value and the actuator strain is 345 kg/cm^2, which corresponds well with the experimental data, and shows that the influence of internal electrodes is minimal in these samples.

Various reliability tests were performed on an IDE actuator without coating. Measurements on a regular plate-through type actuator with polymer coating were recorded for comparison. The test items are as follows:

(A) Thermal cyclic test: 25°C→ 85°C → 25°C → -25°C→ 25°C
(B) Pulse cycle test: Room temperatures. Pre-pressure loading
(C) 25°C/25%RH constant voltage loading
(D) 85°C/90%RH constant voltage loading
(E) 85°C constant voltage loading

With an applied field of 1kV/mm between the electrodes (distance "e" as shown in Figure 10), which is the recommended applied field for commercialized multilayer actuators, the lifetime of the new 3D-IDE actuator was far superior to that of the conventional type. As the applied field increased, however, the reliability parameter became more similar to the conventional type with 1kV/mm applied field. The key failure in the actuators was electrical shorting when humidity was introduced in the environment, which suggested that the failure mode was a combination of electrode migration, particularly silver, and crack formation from the ceramic defects. Since moisture absorption occurs only on the surface of the actuator (or on the polymer coating) according to experiments performed at NEC (17), it is easy to see that the IDE multilayer actuator improves reliability by reducing the area of exposed internal electrode. At the end of March 1992, a 3×10^7 pulse cycle for 180V peak to peak at room temperature was surpassed. The reliability studies are being continued at Tokin Corp.

4. CONCLUSIONS

The history of the development of PZT multilayer actuators was summarized using information collected during the PI's stay in Japan.

Each structure has its own advantages and disadvantages. Comparing the conventional multilayer, multistack actuators, cofiring techniques made the production of numerous inexpensive multilayer actuators possible. The plate-through structure improved the displacement amplitude and mechanical properties of piezoelectric multilayer actuators over the traditional multilayer capacitor configuration, although exposed internal electrodes introduced defects caused by the silver migration under humid conditions. The slit or gap structure actuators, which eliminate the problems in multilayer capacitor and plate-through structure, are currently under development in Japan and will be on the market in the near future.

The new interdigital electrode multilayer actuator gave promising results with the additional advantage of easy displacement multiplication and improved reliability.

Although PZT has been around many years, further understanding of its mechanical properties, at various temperatures, pressures, and different kinds of electrodes are needed to improve the reliability of PZT multilayer actuators.

REFERENCES

1. Private communication with Prof. Chonan of Tohoku University in Japan.
2. Y. Fuda, S. Yoshikawa, T. Yoshida, and T. Ohno, "Ceramic Actuator with Three-Dimensional Interdigital Electrode Structure," to be presented in IEEE International Symposium on the application of Ferroelectrics, Greenville, SC, Aug. 31-Sept. 2, 1992.
3. Yamashita, et al., Proceedings of the 3rd Meeting on Ferroelectric Materials and their Applications, p. 93-95 (1981).
4. NTK Piezoelectric actuator brochure.
5. K. Ohnishi and T. Morohashi, Jpn. J. Ceram. Soc., 98, 895-99 (1990).
6. L.J. Bowen, T. Shrout, W.A. Schulze, and J.V. Biggers, Ferroelectrics, 27, 59-62, (1980).
7. S. Takahashi, A. Ochi, M. Yonezawa, T. Yano, T. Hamatsui, and I. Fukui, Jpn. J. Appl. Phys. Suppl., 22-2, 157-159 (1983), or Ferroelectrics, 50, 181-190 (1983).
8. S. Takahashi, Ferroelectrics, 91, 293-302, (1989).
9. K. Kanayama, H. Mase, H. Saigo, and others, Proceedings of 8th Symposium of Application of Ferroelectrics, p. 137-8, Kyoto, Japan May 29-31, 1991.
10. R.M. White and R.W. Voltmer, Appl. Phys. Lett., 7, 314-316, (1965).
11. K. Yamanouchi, and K. Shibayama, J. Acoust. Soc. Am. 41,1, (1967).
12. S. Hirose, H. Nakamura, H. Shimizu, J. Inst. Elec. Info. Comm. Eng. J71-A, 2093-2101 (1988) (in Japanese).
13. H. Shimizu and T. Yoshida, 5th U.S.-Japan Seminar Dielec. Piezoelec. Ceram., Kyoto, Japan, Abstract III-17, p. 250-252 (1990).

14. Japanese patent Koho No. 89-14981.

15. Japanese patent Koho No. 91-94487.

16. S. Hirose, Ph.D. dissertation, Tohoku University (1988) (in Japanese).

17. K. Morimoto, S. Tagami, and M. Inagawa, NEC Technical Report, 44, 132-137, (1991) (in Japanese).

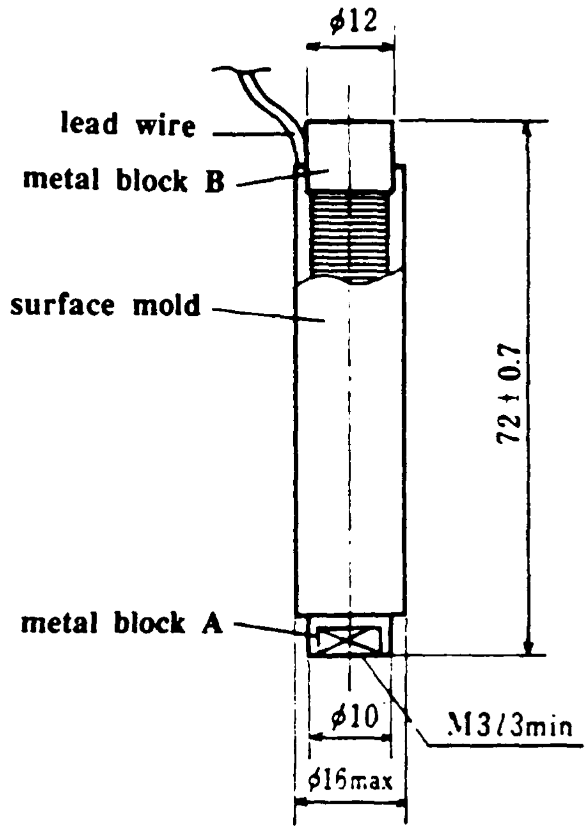
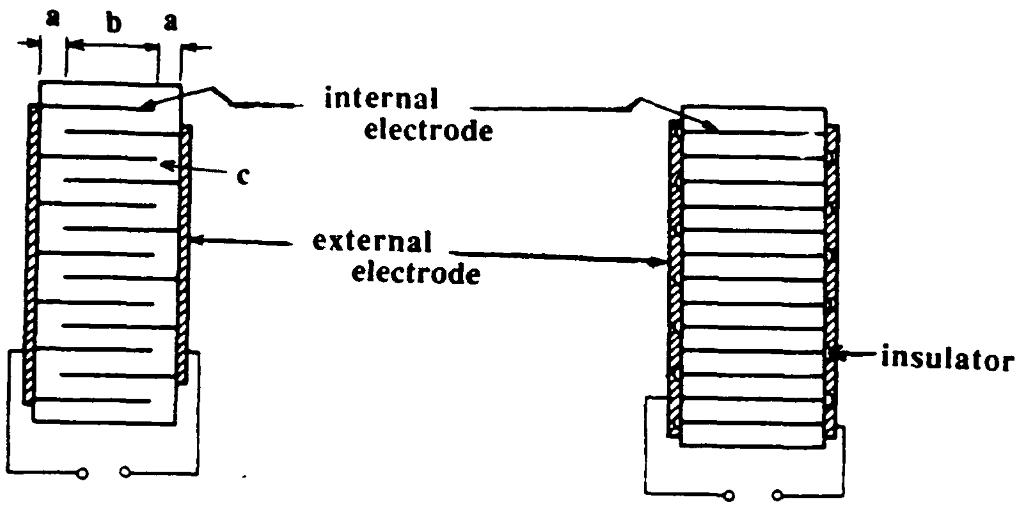
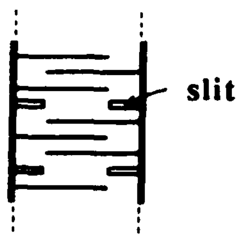


Figure 1. NTK's Piezostack

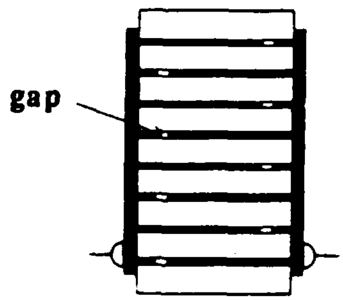


(A) MLC type

(B) Plate-through type



(C) MLC with slit type



(D) Gap type

Figure 2. Various Multilayer Actuator Structures.

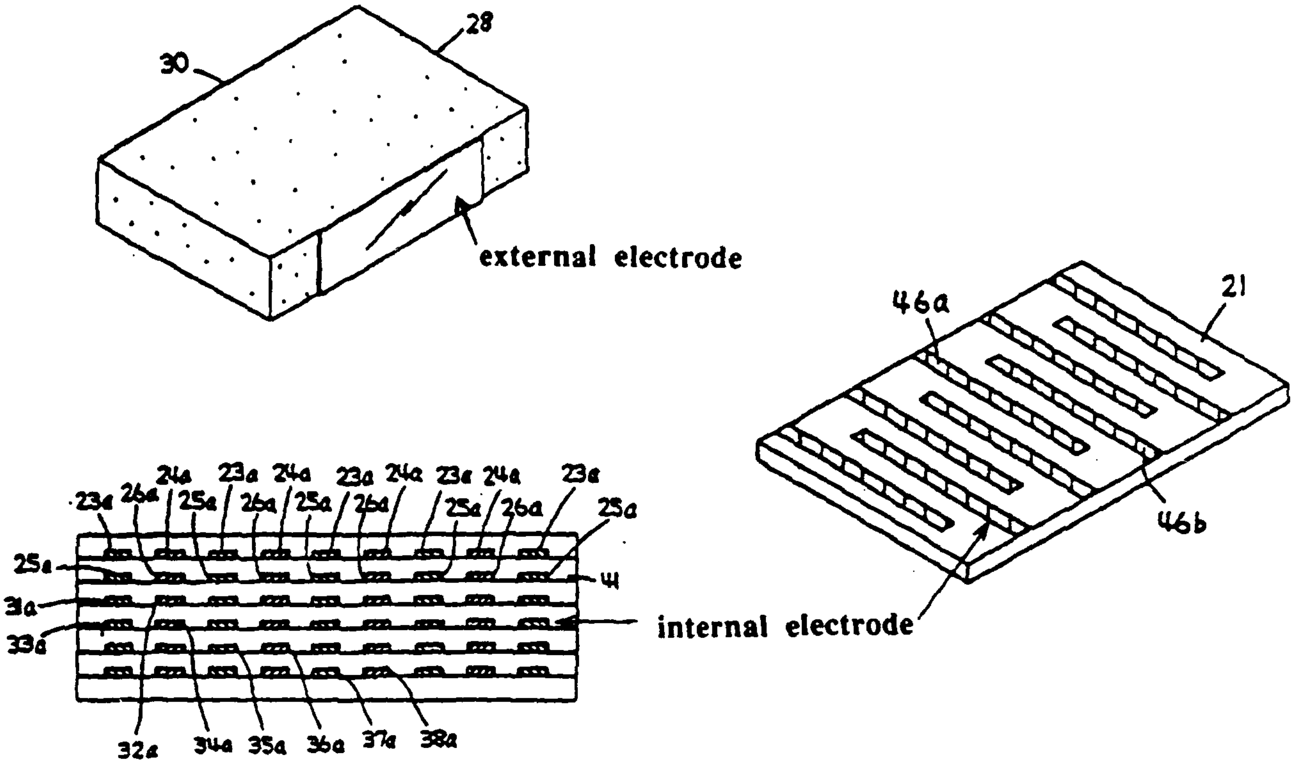


Figure 3. Figures from Japanese Patent No. 89-14981 showing the IDE structure.

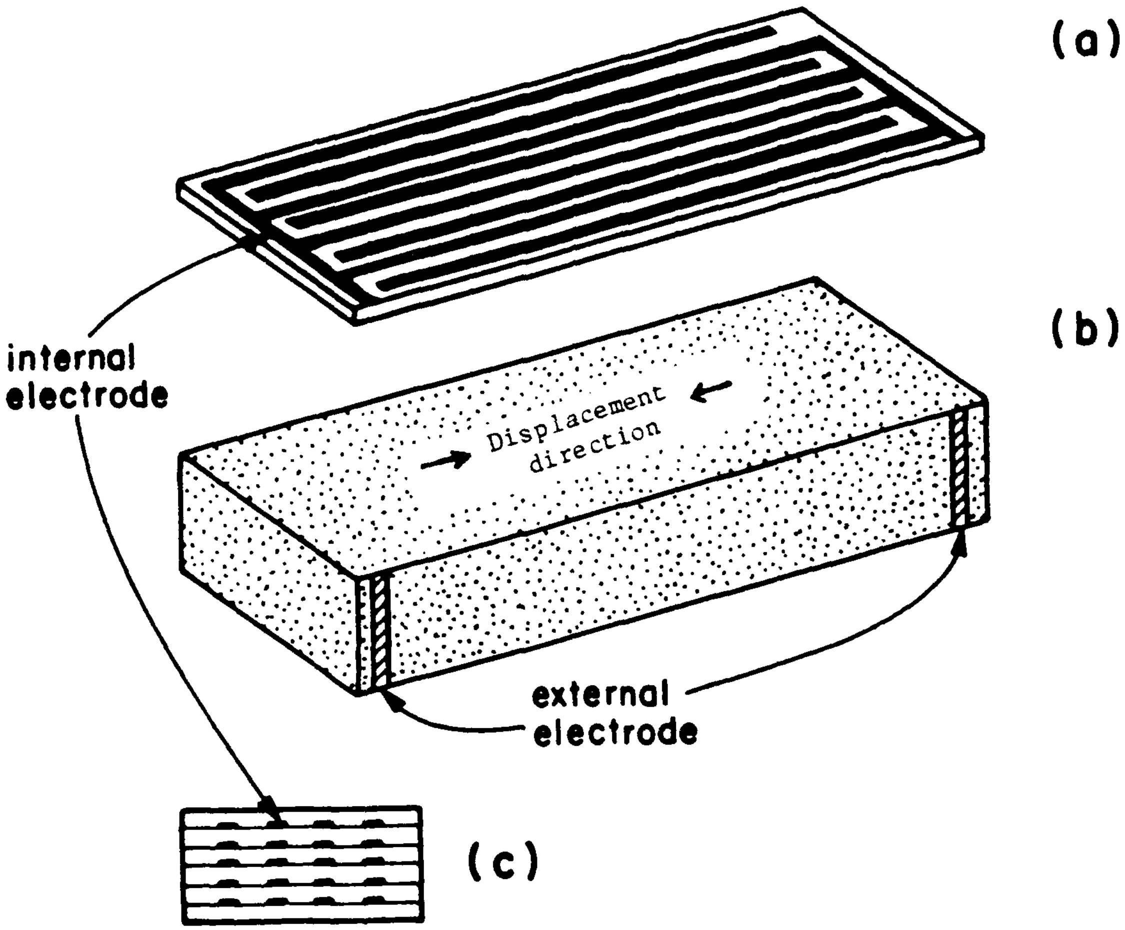


Figure 4. Transverse-effect actuators using IDE electrode.

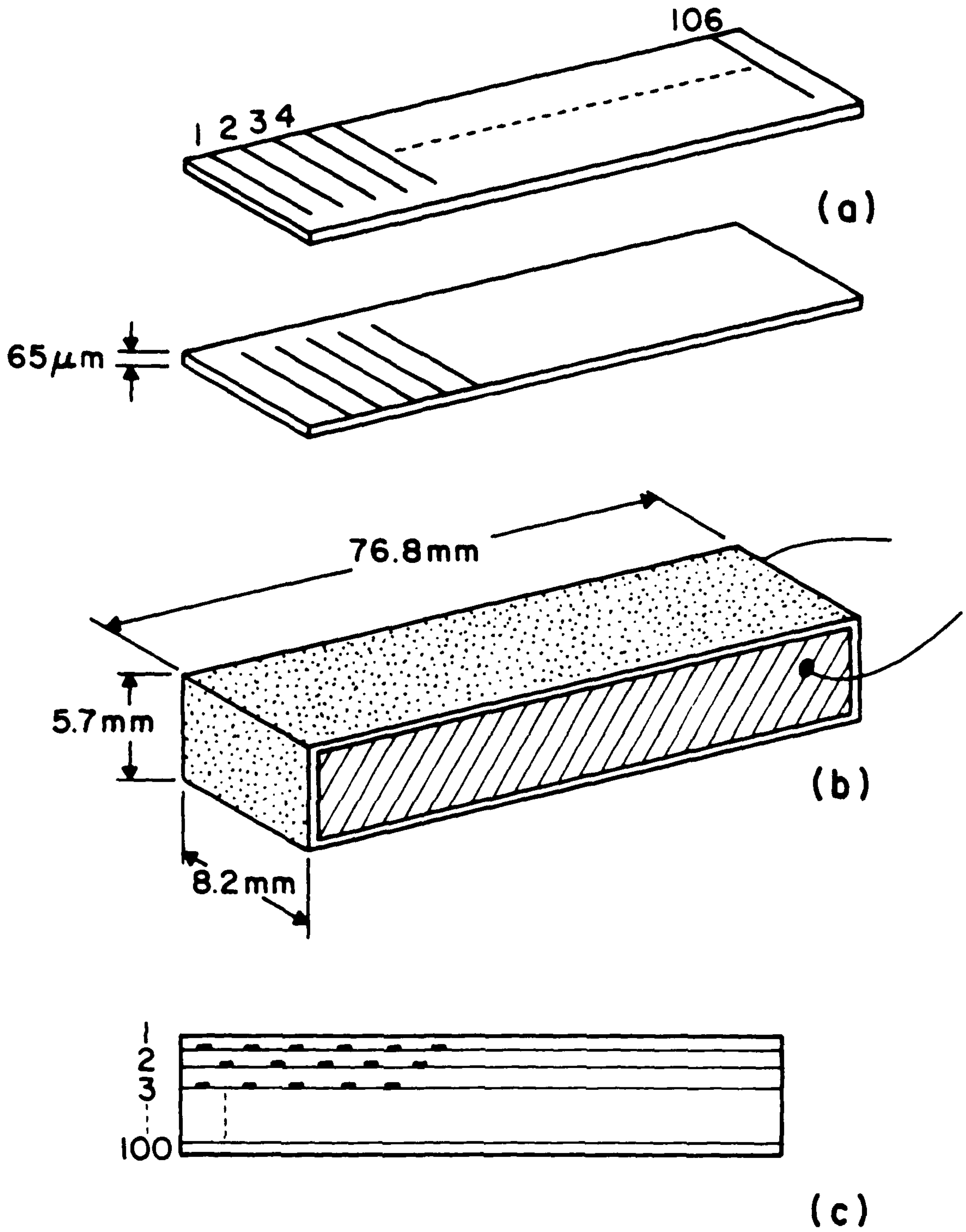


Figure 5. Schematic diagram of 3D-IDE actuators
a. Green sheets configuration
b. Fired and electroded sample
c. Section view of (b)

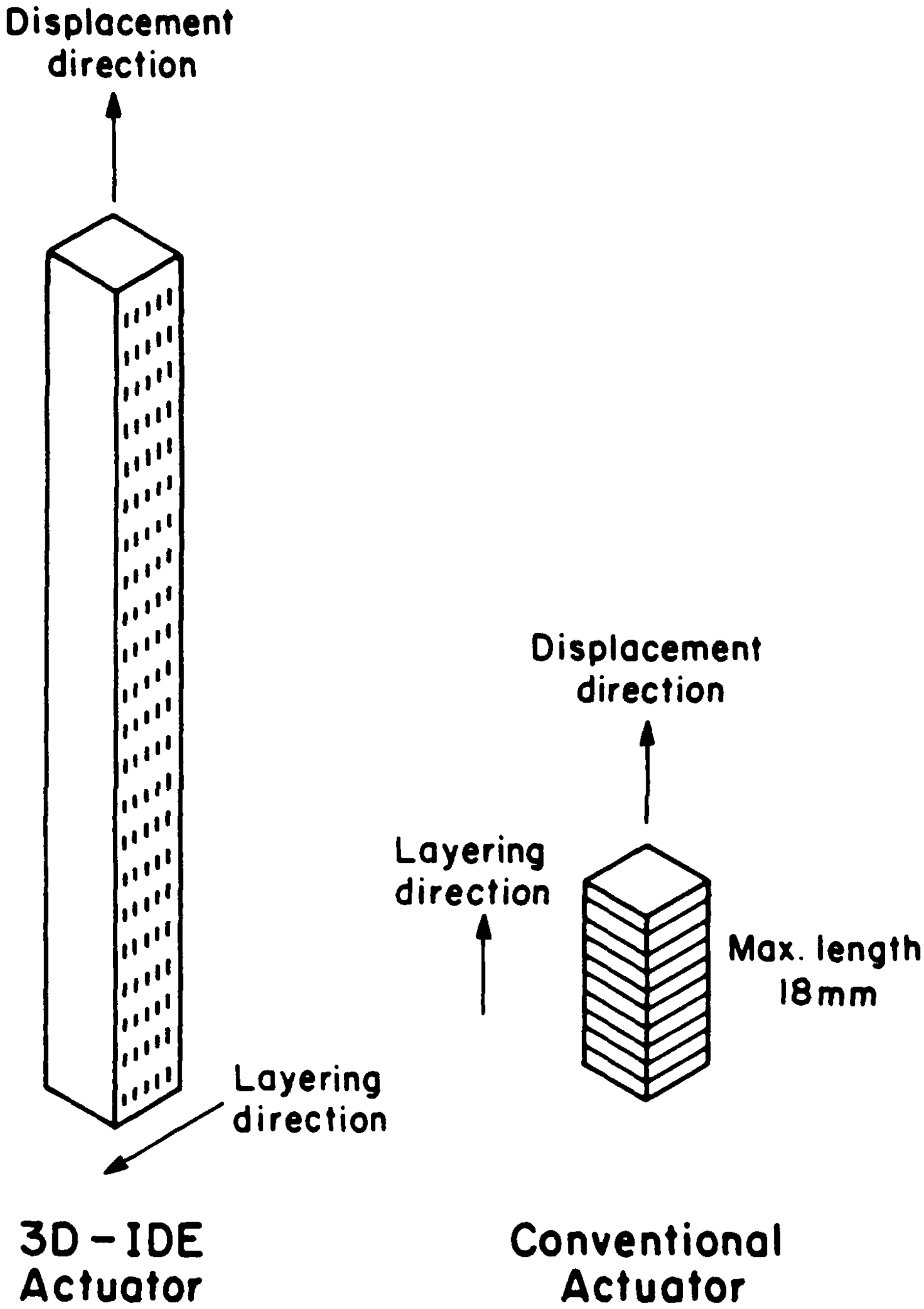


Figure 6. Schematic diagram comparing 3D-IDE actuators with conventional multilayer actuators.

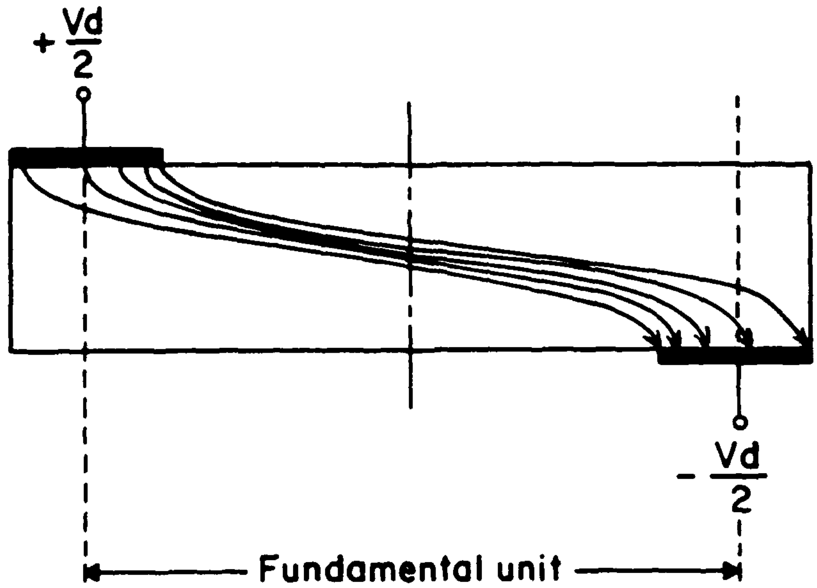


Figure 7. Cross section of fundamental unit of 3D-IDE actuator with lines of electric force.

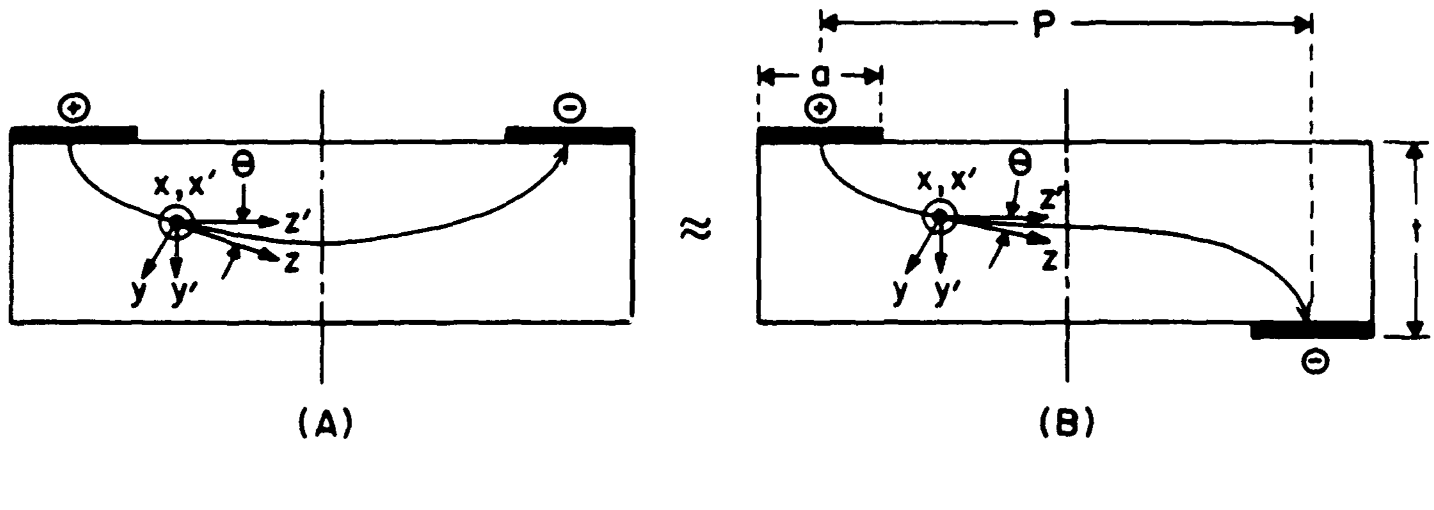


Figure 8. Fundamental unit model (A) from reference 16 and (B) 3D-IDE actuator sample.

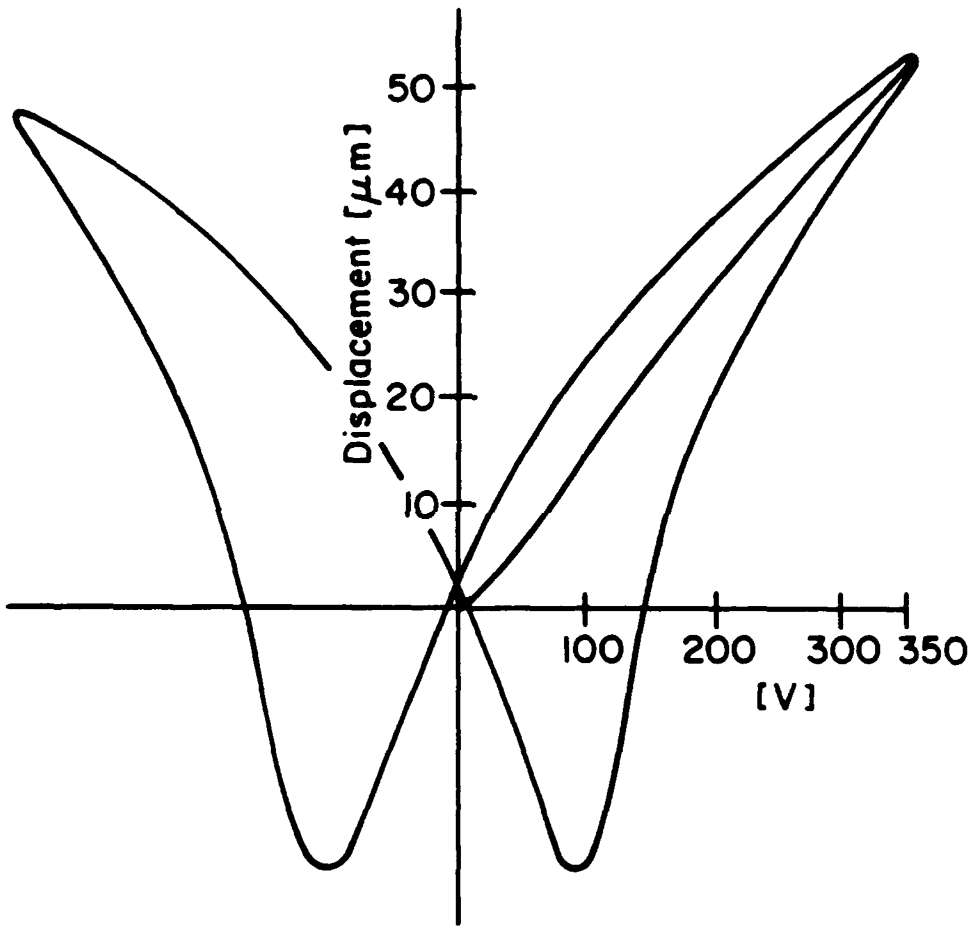


Figure 9. Displacement with applied voltage of typical 3D-IDE actuator sample.

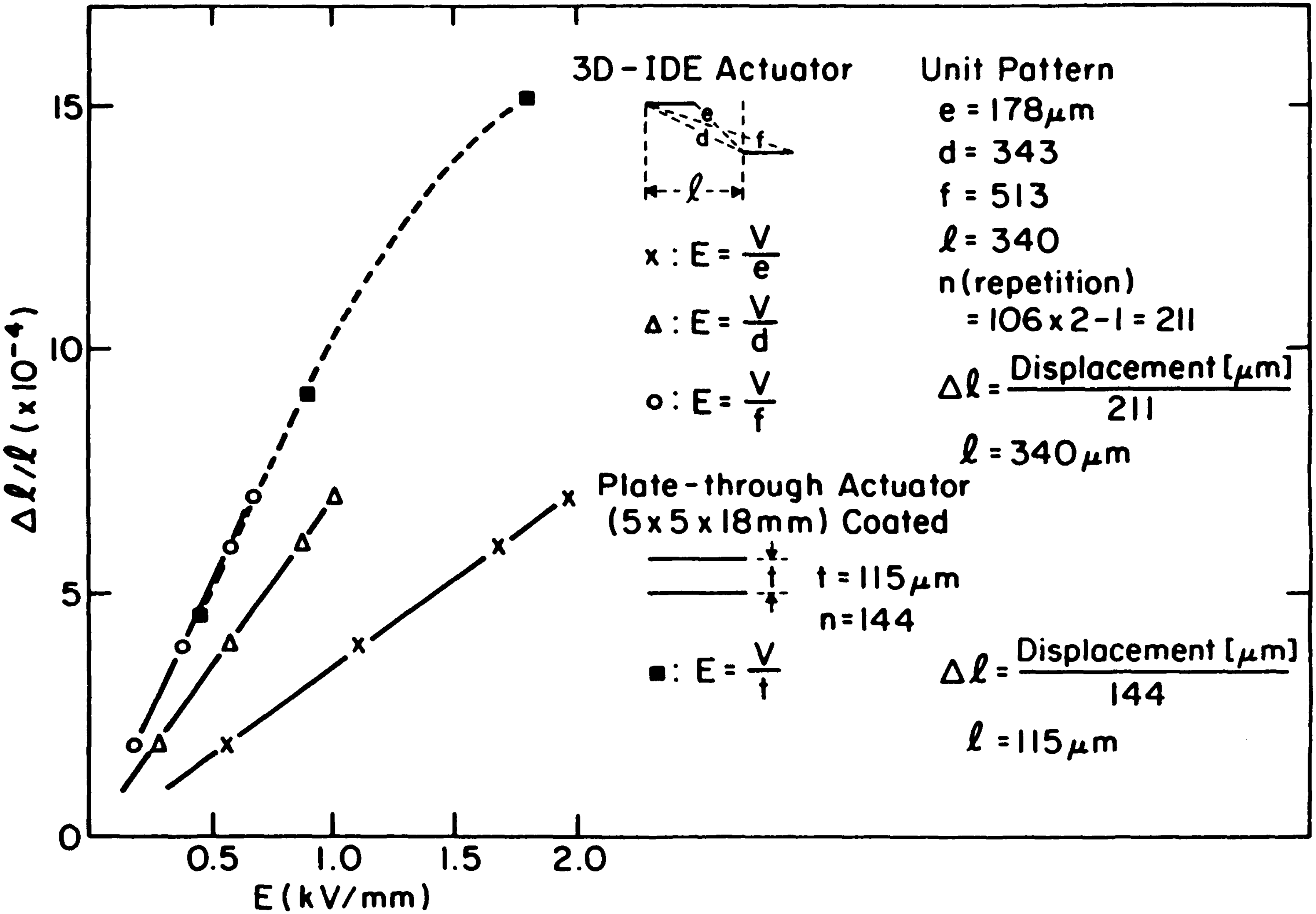


Figure 10. Electric field induced strain of 3D-IDE actuator using three different electrode distances, d,e, and f (solid lines) and commercial plate-through type multilayer actuator (dotted line).

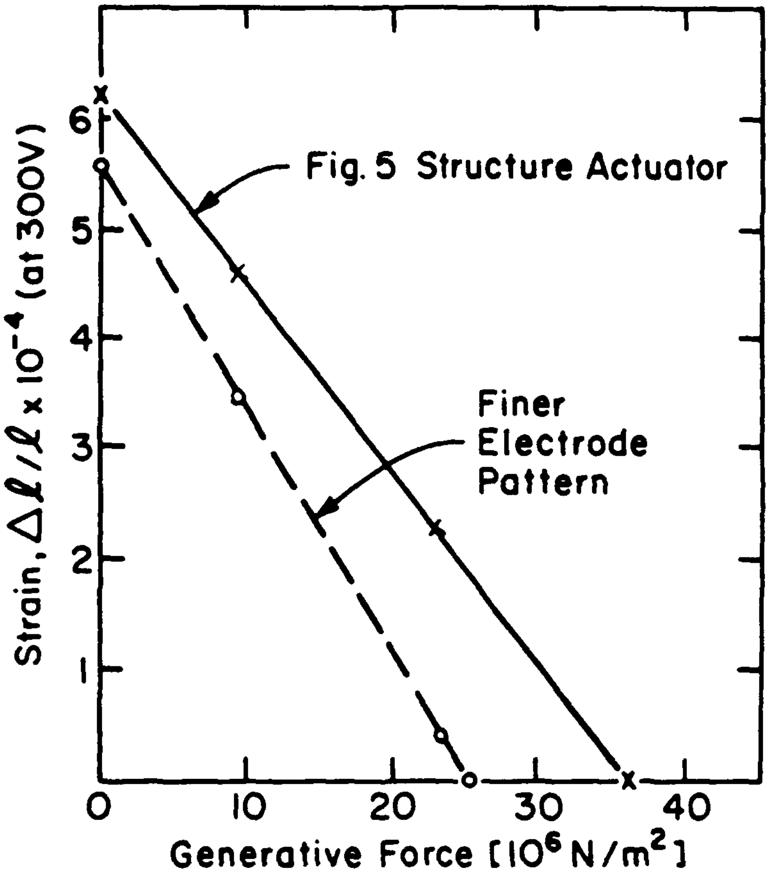


Figure 11. Relationship between generative force and strain of 3D-IDE actuators.