



## CHAPTER IV

### ELECTROMECHANICAL RESPONSES OF A CROSS-LINKED POLYDIMETHYLSILOXANE

#### 4.1 Abstract

A high molecular weight polydimethylsiloxane, PDMS, gel was prepared and investigated as an electroactive polymer actuator. Electromechanical properties of the PDMS gels were measured under an oscillatory shear mode at the temperature of 27 °C to determine the effects of crosslink ratio and electric field strength. The storage modulus,  $G'$ , of PDMS gel increases linearly with crosslink density but nonlinearly with electric field. The increase in the storage modulus with crosslink density is due to the increase in the number of junction points and strands. With increasing electric field strength, the storage modulus increases as the electric field induces dipole moments generating the electrostatic forces within the matrices. The gel with the crosslink ratio of 0.01 possesses the highest  $G'$  sensitivity of 41% at 2 kV/mm. The temporal response of PDMS gels upon repeated applications of electric field strength of 2 kV/mm was investigated. For the crosslink PDMS ( $N_c/N_m = 0.01$ ) system, at the electric field of 2 kV/mm,  $G'$  immediately increases and rapidly reaches a steady-state value. With electric field off,  $G'$  decreases and nearly recovers its original value. The crosslinked PDMS ( $N_c/N_m = 0.01$ ) is nearly a reversible system. Finally, we investigated the bending response of the PDMS films, suspended in silicone oil between copper electrodes. From the deformation data, we estimated the dielectrophoresis force,  $F_D$ , to be a linear function of electric field strength.

#### 4.2 Abbreviation

$E_0$	applied electric field strength
$G'$	storage modulus (Pa/s)
$G''$	loss modulus (Pa/s)
$t_{ind}$	induction time

$t_{\text{rec}}$	recovery time
$\phi$	volume fraction
$\alpha$	scaling exponent
$\gamma$	scaling exponent
$\sigma$	electrical conductivity
$R$	resistant
$t$	disk thickness
$K$	geometric correction factor
$\beta$	relative polarizability
$K_f$	dielectric permittivity of medium
$\eta^*$	complex oscillatory steady shear viscosity
$\omega$	frequency
$F_D$	dielectrophoresis force
$F_d$	elastic deflection force
$N_c$	mole of crosslinker
$N_m$	mole of monomer
$v_1$	the molar volume of solvent ( $M_w/\text{density}$ )
$w_o$	the original polymer weight
$w_s$	the swollen polymer weight
$\chi$	the polymer-solvent interaction parameter
$R$	the universal gas constant, 8.29 N <sub>m</sub> /mol.K,
$\delta$	the solubility parameter
$v$	number density of strands

### 4.3 Introduction

Electroactive polymers (EAP) have emerged in the last decade as promising actuation materials in the field of muscle/insect-like actuators, robotics, and etc. The novel characters EAP are light-weight, high energy density, and high flexibility; all are suitable properties for an artificial muscle (Gobin *et al.*, 2002). EAP can be divided into two major categories based on their activation mechanisms: electronic

and ionic. Coulomb forces drive the electronic EAP, which includes the electrostrictive, the electrostatic, the piezoelectric, or the ferroelectric behaviors. This type of EAP materials can be made to withstand a large induced displacement while they are activated under DC voltage. In contrast to the electronic EAP, ionic EAPs are materials that involve mobility or diffusion of ions; they generally operate between two electrodes and in an electrolyte (Cohen, 2000).

Dielectric EAP is the one of electronic EAP in which an electric field can be applied to induce a large actuation strain while possessing low elastic stiffness and high dielectric constant. It has been reported that polydimethylsiloxane, PDMS, elastomer can easily bend under applied electric field (Rubinstein *et al.*, 2003). In our work, we are interested in investigating the electromechanical properties of PDMS: the storage modulus response, the temporal response, the bending response, and its induced electrical force generated between two electrodes.

## 4.4 Experimental Details

### 4.4.1 Materials

High molecular weight hydroxyl terminated PDMS's (viscosity 18,000 – 20,000 cSt, Aldrich) were used as the polymer matrices. Tetraethyl orthosilicate (AR grade, Aldrich) and dibutyl tin dilaurate (AR grade, Aldrich) were used as the initiator and the catalyst, respectively. Silicone oil was purchased from Aldrich (viscosity 100 cSt, Aldrich).

### 4.4.2 Preparation of PDMS Gel and Electromechanical Property Measurement

Electromechanical properties of PDMS under an oscillatory shear at fixed temperature of 27 °C were measured in order to investigate the effects of crosslinking ratio and electric field strength. To study the effect of crosslinking ratio, PDMS at various crosslink ratios ( $N_c/N_m = 0.001, 0.003, 0.005, 0.01, 0.03$  and  $0.05$ : where  $N_c$  is moles of initiator and  $N_m$  is moles of PDMS), were prepared by mixing the high molecular weight hydroxyl terminated PDMS, tetraethyl orthosilicate, and dibutyl tin dilaurate at various initiator moles. The mixture was cast in a mold

(diameter = 25 mm and height = 1 mm) and dried under vacuum at room temperature (27 °C) for 6 hrs. Electromechanical properties of PDMS under an oscillatory shear at fixed temperature of 27 °C were measured (Rheometric Scientific Inc., ARES). The dynamic moduli,  $G'$  and  $G''$ , were measured as functions of frequency and electric field strength. The linear viscoelastic regime was determined by the strain sweep test to determine the appropriate strain to be used to measure  $G'$  and  $G''$ . Frequency sweep test was then carried out measure  $G'$  and  $G''$  as functions of frequency (0.1 -100 rad/s) at fixed strains of 700% and 1% for pure PDMS fluid and for the crosslinked PDMS (crosslink ratios of 0.001, 0.003, 0.005, 0.01, 0.03 and 0.05), respectively. Pre-oscillatory shear at frequency of 1 rad/s, at fixed strains at 700% and 1% for pure PDMS fluid and for the crosslinked PDMS, under electric field (~10 min) was applied to the sample to ensure an equilibrium polarization before each measurement was taken.

#### 4.4.3 Determination of $M_c$

The average molecular weight between crosslinks of the PDMS gels,  $M_c$ , was determined from the swelling in HPLC grade toluene at room temperature (Demanze *et al.*, 1996). The version of the Flory-Rehner equation (Demanze *et al.*, 1996) was used for our PDMS systems:

$$M_c = - \frac{v_1 \rho_2 \left( v_{2m}^{1/3} - \frac{v_{2m}}{2} \right)}{\left[ \ln(1 - v_{2m}) + v_{2m} + \chi_1 v_{2m}^2 \right]} \quad (4.1)$$

$$\text{where } v_{2m} = \frac{w_0}{v_{equil} \times \rho_2} \quad (4.2)$$

$$v_{equil} = \frac{w_0}{\rho_2} + \frac{w_s - w_0}{\rho_1} \quad (4.3)$$

$$\chi = 0.34 + \frac{v_1}{RT} (\delta_1 - \delta_2)^2 \quad (4.4)$$

and where  $v_1$  is the molar volume of solvent ( $M_w/\text{density}$ ),  $\rho_2$  is the polymer density, PDMS equal to 0.97 g/cm<sup>3</sup>,  $\rho_1$  is the solvent density or of toluene which is equal to 0.867 g/cm<sup>3</sup>,  $w_0$  is the original polymer weight,  $w_s$  is the swollen polymer weight,  $\chi$

is the polymer-solvent interaction parameter,  $R$  is the universal gas constant,  $8.29 \text{ N}_m/\text{mol.K}$ ,  $T$  is the absolute temperature,  $298 \text{ K}$ ,  $\delta_1$  is the solubility parameter of PDMS which is equal to  $19.4 \text{ (MPa)}^{1/2}$ , and  $\delta_2$  is the solubility parameter of toluene which is equal to  $18.20 \text{ (MPa)}^{1/2}$ .

#### 4.4.4 Deflection Measurement

To study the elastic response of the PDMS gels to an electric field, films of the PDMS gels were vertically suspended into silicon oil between a pair of parallel copper electrode plates (40 mm long, 30 mm wide, and 1 mm thick). A rigid plastic thread was used to fix the top position of the gel (as shown in Figure 3). A high dc voltage was applied in a non-contact mode through the electrodes, which were 10 mm apart. The electric bending response of the gel was recorded by a video camera, and the deflection properties were analyzed by a digital image analyzer (Panasonic M3000, Japan). Both the voltage and the current were monitored as well. All the measurements were carried out at ambient temperature ( $27 \text{ }^\circ\text{C}$ ).

## 4.5 Results and Discussion

### 4.5.1 Electrorheological Properties of Pure Polydimethylsiloxane

#### 4.5.1.1 *Effect of Crosslinking in the Absence of Electric Field*

The effect of crosslinking on the rheological properties of pure polydimethylsiloxane (PDMS) was first investigated. The crosslinking ratios are 0.001, 0.003, 0.005, 0.01, 0.03 and 0.05 and the number density of strands,  $\nu$  was determined from the relation  $\nu = \rho N_{av}/M_c$ .  $\nu$  or the numbers of chemical strands per volume are equal to  $3.7 \times 10^{19}$ ,  $5.75 \times 10^{19}$ ,  $1.00 \times 10^{20}$ ,  $1.15 \times 10^{20}$ ,  $1.27 \times 10^{20}$ , and  $1.40 \times 10^{20}$  #strands / $\text{cm}^3$  for PDMS's with the crosslinking ratios of 0.001, 0.003, 0.005, 0.01, 0.03, and 0.05, respectively. The storage modulus of crosslink PDMS gels measured is independent of frequency, indicative of the gel nature. Thus, in the following, the storage modulus data will be presented only at frequency of 1 rad/s and at strain equal to 1%. Figures 4.1 (a) shows the dependence of the storage modulus,  $G'$ , of PDMS on the number density of strands,  $\nu$ , without electric field

applied at a strain equal to 1%. In an absence of electric field,  $G'$  initially increases almost linearly with the strand density,  $\nu$ , up to  $1.0 \times 10^{20}$  strands/cm<sup>3</sup>, consistent with the classical network theory (Perlin *et al.*, 1998):

$$G \equiv \frac{nk_B T}{V} = \nu k_B T \quad (4.5)$$

where  $k_B$  is the Boltzmann's constant,  $T$  the absolute temperature (K), and  $\nu$  is number of strands per unit volume (1/cm<sup>3</sup>),  $\rho N_{av}/M_c$ . Above  $1.15 \times 10^{20}$  strands/cm<sup>3</sup>,  $G'$  evidently increases non-linearly with  $\nu$ .

#### 4.5.1.2 Effect of Crosslinking under Electric Field

The effect of electric field strength on the rheological properties of pure polydimethylsiloxane (PDMS), at various crosslinking ratios, was investigated in the range of electric field strength between 0-2 kV/mm. The storage modulus  $G'$  (Pa) of each crosslinked PDMS system increases linearly with strand density, as shown in Figure 4.1 (a). As a sufficiently high electric field strength is applied, dipole moments are generated leading to the electrostatic interaction between different strand segments in the matrix (Perlin *et al.*, 1998 and Kornbluh *et al.*, 2002). In addition, a voltage differential between the electrodes can generate electromagnetic forces that act to pull the electrode together (Perlin *et al.*, 1998 and Puvanattvattana *et al.*, 2006). This attraction causes a compressive force on the dielectric elastomeric in the direction of the electric field throughout the volume between the electrodes (Puvanattvattana *et al.*, 2006). The resulting effective pressure can be written as:

$$P = \epsilon_0 \epsilon_r E^2 \quad (4.6)$$

where  $\epsilon_0$  and  $\epsilon_r$  are the permittivity of free space and the relative permittivity of polymer, respectively (Puvanattvattana *et al.*, 2006). Figure 4.1 (b) shows the storage modulus responses ( $\Delta G'$ ) vs. electric field of PDMS systems of various crosslinking ratios at frequency of 1 rad/s, and at strain equal to 1%.  $\Delta G'$  increases with electric field up to  $E = 1$  kV/mm, beyond that electric field strength it levels off and becomes saturated at  $E = 2$  kV/mm.  $\Delta G'$ , at a given  $E$ , is generally larger for a PDMS system with a higher crosslinking ratio. Theoretically, we expect  $\Delta G'$  to show a quadratic

dependence with E, corresponding to the model proposed by Perline *et al.* (1998).

We next investigated the maximum G' sensitivity the PDMS systems. The sensitivity is defined as  $\Delta G'/G_o = (G'_E - G'_o)/G'_o$ , where  $G'_E$  is the G' value of system under electric field, and  $G'_o$  is the G' value of system without electric field. The G' sensitivity of the PDMS systems with the crosslinking ratios of 0.001, 0.003, 0.005, 0.01, 0.03 and 0.05 at electric field strength of 2 kV/mm are 7%, 22%, 35%, 41%, 27% and 9%, respectively. Thus, the PDMS with the crosslinking ratio of 0.01 ( $\nu = 1.15 \times 10^{20}$  number of strands /cm<sup>3</sup>) possesses the highest G' sensitivity. This result suggests that the system with the crosslinking ratio of 0.01 has moderate flexibility within the matrix in the absence of electric field such that its structure rigidity can be induced further by electric field. On the other hand, the lower crosslinked systems have a more fluid-like structure; free movement and relaxation of polymer chains are still allowed in the presence of electric field and they possess smaller responses. The higher crosslinked systems contain relatively smaller free volumes and have more rigid structures; they simply cannot respond further to or increase their rigidity further under the applied electric field.

#### 4.5.2 Time Dependence of the Electromechanical Response

We next investigated the temporal characteristic of crosslinked PDMS ( $N_c/N_m = 0.01$ ) under electric field strengths of 1 and 2 kV/mm. The temporal characteristic of each sample was measured in the linear viscoelastic regime at a strain of 1 %, and at frequency of 1 rad/s. Figure 4.2 shows the change in G' of crosslinked PDMS ( $N_c/N_m = 0.01$ ) on electric field strength of 1 and 2 kV/mm during a time sweep test, in which an electric field is turned on and off alternately. G' immediately increases and rapidly reaches a steady-state value. When the electric field is off, G' decreases and nearly recovers its original value. Thus, the crosslinked PDMS ( $N_c/N_m = 0.01$ ) is nearly a reversible system. The time required for G' to reach the steady-state value on applying the field is called the induction time,  $t_{ind}$  and the time required for G' to decay towards its steady-state value when the electric field is turned off is called the recovery time,  $t_{rec}$ .  $t_{ind}$  are 290,280 and 273 s, and the  $t_{rec}$  are 150, 138 and 125 s for the PDMS systems with crosslinking ratios of 0.01, 0.03 and

0.05, respectively. The decrease of  $t_{ind}$  with the crosslink density suggests that at a higher strand density ( $\nu$  more than  $1.15 \times 10^{20}$  chemical strands /cm<sup>3</sup>,  $N_c/N_m = 0.01$ ), the system possesses a more solid like behavior, thus it requires a shorter time to reach the equilibrium state and to relax back to its original state.

#### 4.5.3 Deflection under Electric Field

Finally, we investigated the effect of crosslinking ratio and electric field strength on the deflection of soft and flexible crosslinked PDMS films. The amount of deflection of the PDMS films at a specific electric field strength can be described by parameters  $d$ ,  $l$  and  $\theta$  as shown in Figure 4.3. Figure 4.4 illustrates the effect of electric field strength on the bending of the PDMS film ( $N_c/N_m = 0.01$ ), 1 mm x 3mm x 18 mm, suspended in the silicone oil (100 cSt). When an external electric field is applied, the crosslinked PDMS film responds with a significant and rapid bending towards the anode with the amount of bending dependant on the electric field strength, indicating the attractive interaction between the anode and the polarized PDMS. Under electric field, the crosslinked bridges and the strands in the PDMS network inevitably change their molecular conformations due to the resultant dielectrophoresis force exerted by the electrodes, leading to a macroscopic shape change and/or motion (Verga *et al.*, 2005). As the electric field is removed, the crosslinked PDMS nearly recovers its original position and shape due to the gravitational force, its elasticity, and the reversible polarized PDMS. Thus, the crosslinked PDMS ( $N_c/N_m = 0.01$ ) is also a reversible bending system, consistent with the  $G'$  temporal response results.

The values of the observed bending parameters,  $d$ ,  $l$  and  $\theta \approx \arctan(d/l)$  of the crosslinked PDMS films at various electric field strength are tabulated in Table 4.1. The displacement of the free bottom end of the gel ( $d$ ) and the degree of bending ( $\theta$ ) increase linearly with electric field strength. As the electric field is applied, the freely suspended end of the PDMS films bend towards the anode site because the attractive interaction between the anode and the dipole moments set up in the matrix. As a higher electric field strength is applied, stronger dipole moments are expected to be generated leading to a higher degree of bending obtained. In Figure 4.5a, the degree



of bending ( $\theta$ ) is plotted in linear scale versus electric field strength in order to investigate the effect of crosslinking ratio.  $\theta$  of both crosslinked PDMS systems linearly increases with electric field strength. However, we may identify the electrical yield point at electric field strength of 100 V/mm for the low crosslinking ratio,  $N_c/N_m = 0.001$  system. The electrical yield point is defined as the necessary electric field strength required to bend a crosslinked PDMS film. Because the lower crosslinked system has a lower number of strands in the PDMS network, it thus has a lower ability to generate the dielectrophoresis forces; thus it requires a higher field strength to change its molecular conformation. Filipcsei *et al.* reported a similar effect for the weakly crosslinked PDMS gels containing finely distributed  $\text{TiO}_2$  suspended in silicone oil (DC 200, Fluka) under action of external electric field (Filipcsei *et al.*, 2000). They discovered a driving mechanism to induce deformation and movement of neutral polymer gels in non-conducting medium. Since the particles cannot leave the gel matrix, all force acting on the particles are directly transmitted to the polymer chains resulting in either the locomotion or the deformation of the gel (Filipcsei *et al.*, 2000). With increasing field intensity, the deflection of the free end of the gel increases. At small field intensities ( $< 3$  kV/cm), the relationship between the deflection and electric field strength can be approximated to be linearly dependent. The elastic response of another elastomer, a polyurethane (PUE) under external electric field, was studied by Ueda *et al.* (1997). They reported the bending displacement of a PUE sheet under electric field applied through 2 electrodes at one end. The displacement was due to the dipole moments of the ester linkages within in the polymer chain induced by the electric field (Ueda *et al.* 1997).

We next investigate the dielectrophoresis force,  $F_D$ , produced by the electric field through the crosslinked bridges and the strands within the PDMS network, which is responsible for the change in the PDMS molecular conformation or the macroscopic shape change and/or motion (Verga *et al.*, 2005).  $F_D$  can be calculated from the static force static balances between the weight of the sample and the elastic deflection force,  $F_d$ . The resultant  $F_D$  can be written as:

$$F_D = mg \sin \theta + F_d \quad (4.7)$$

where  $F_d$  is the elastic deflection force required to produce a bending as can be derived from the theory of linear elasticity (Puvanattvattana et al., 2006):

$$v(y = 0, x = 0) = \frac{F_d l^3}{3EI} \quad (4.8)$$

where  $v$  is the displacement of the free bottom end of PDMS film,  $E$  is the Young's modulus which is equal to  $2G(1+\nu)$ ,  $G$  is the shear modulus (taken to be  $G'(\omega = 1 \text{ rad/s}) \approx 12,000$  and  $22,000$  Pa for crosslinking ratios of 0.001 and 0.01, respectively),  $\nu$  is the Poisson's ratio ( $=0.5$  for incompressible sample),  $I$  is the moment of inertia  $\frac{1}{12}t^3w$ ,  $t$  is the thickness of PDMS film,  $w$  is the width of PDMS film, and  $l$  is the length of PDMS film (Timoshenko *et al.*, 1970). Table 4.1 shows the calculated  $F_D$  values of the crosslinked PDMSs at various electric field strengths and crosslinking ratios. For each crosslinked system,  $F_D$  increases linearly with electric field strength as shown in Figure 4.5(b). A higher electric field strength induces a larger dielectrophoresis force onto the PDMS sample thus a larger degree of bending is produced. In Table 4.1, the last column, we also calculated the deflection force,  $F'_d$ , from the nonlinear elasticity theory (Gere *et al.*, 1991) in which the bending produces a curvature on the beam. Both deflection forces,  $F_d$  and  $F'_d$ , are quite comparable in magnitude. The linear deflection force  $F_d$  is believed to be more accurate since the bending observed occurs mostly at the clamped end and no sample curvature can be visibly identified.

Feher *et al.* (2001) reported a dependence of applied voltage on the dielectrophoresis force of crosslinked PDMS gels containing  $\text{TiO}_2$  suspended in silicone oil. They found that electrophoresis force was proportional to electric field square,

$$\rho_f = \frac{f_{DEP}}{r^2 \pi} = \frac{CVV}{r^2 \pi d} = \text{const}V^2 \quad (4.9)$$

where  $\rho_f$  is the force density ( $\text{N}/\text{cm}^2$ ),  $f_{DEP}$  is the dielectrophoresis force (N),  $r$  is the radius of cylindrical PDMS gel (cm),  $C$  is capacitance (C/V),  $V$  is the applied voltage (kV) and  $d$  is the gap distance between the two parallel electrodes (cm). The result differs from our; this may originate from the filled polarizable particles,  $\text{TiO}_2$ , which can respond to an external electric field, leading to a larger electrophoresis

force and the quadratic dependence. Our system with a crosslinking ratio of 0.01 shows a higher  $F_D$  than the system with a crosslinking ratio of 0.001. The former system has a larger number of strands and it is more susceptible to the dielectrophoresis force (Varga *et al.*, 2005).

Next we observed the response time of each crosslinked PDMS at various electric field strength. The induction time ( $t_{ind}$ ) is the time required for PDMS films to reach the steady-state bending when applying the field. The time required for PDMS films decay toward its original point when the electric field is turned off is called the recovery time,  $t_{rec}$ . For each crosslinked PDMS film,  $t_{ind}$  decreases and  $t_{rec}$  increases with electric field strength, as shown in Table 1. The increase of  $t_{rec}$  with electric field indicates a longer relaxation time required to recover its original shape from a greater deformed state.

#### 4.6 Conclusions

In the absence of electric field, the storage modulus of the PDMS systems increases linearly with crosslinking density due to the larger number of strands. For electric field strength between 0.5 to 2.0 kV/mm, storage modulus increases nonlinearly with electric field. For the  $G'$  temporal characteristic of the crosslinked PDMS ( $N_c/N_m = 0.01$ ) under electric field strengths of 1 and 2 kV/mm, data indicate that it is nearly a reversible system consistent with the deflection experiment. The degree of bending of the PDMS films and the dielectrophoretic forces  $F_D$ , increase linearly with electric field strength. Moreover, we observed the electrical yield point at electric field strength of 100 V/mm for the lower crosslinked PDMS ( $N_c/N_m = 0.001$ ).

#### 4.7 Reference

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**Table 4.1** Effect of electric field strength on electrostiction behavior of PDMS films

Sample	E (V/mm)	l (cm)	d (cm)	$\theta$ (degree)	$t_{wd}$ (s)	$t_{wc}$ (s)	$mgsin\theta$ ( $\times 10^{-4}$ )	$F_d$ ( $\times 10^{-6}$ N)	$F'_d$ ( $\times 10^{-5}$ N)	$F_0$ ( $\times 10^{-4}$ N)
PDMS ( $N_e/N_m = 0.01$ )	0	1.78								
$m = 0.097$ g	100	1.78	0.16	5.1	19	3.9	0.96	0.524	0.10	1.01
$t = 0.00072$ m	200	1.75	0.28	9.2	16	4.8	1.72	0.98	0.87	1.82
$w = 0.003$ m	300	1.75	0.35	11.4	14	5.5	2.12	1.21	1.07	2.24
$l_0 = 0.0178$ m	400	1.67	0.46	13.5	11	7.6	2.51	1.59	2.14	2.67
	500	1.53	0.47	17.1	5	12.1	3.16	2.43	3.50	3.41
PDMS ( $N_e/N_m = 0.001$ )	0	1.80								
$m = 0.107$ g	100	1.80								
$t = 0.00069$ m	200	1.79	0.13	4.1	13	4.1	0.76	0.25	0.41	0.78
$w = 0.0031$ m	300	1.78	0.16	5.1	11	5.3	0.93	0.31	0.59	0.96
$l_0 = 0.018$ m	400	1.75	0.32	10.4	7	8	1.87	0.61	0.82	1.94
	500	1.68	0.41	13.7	3	12	2.48	0.79	1.40	2.56

$m$  is the weight of PDMS sample

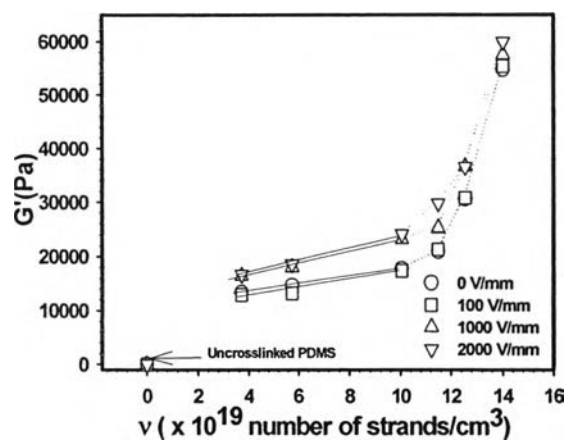
$t$  is the thickness of PDMS film

$w$  is the width of PDMS film

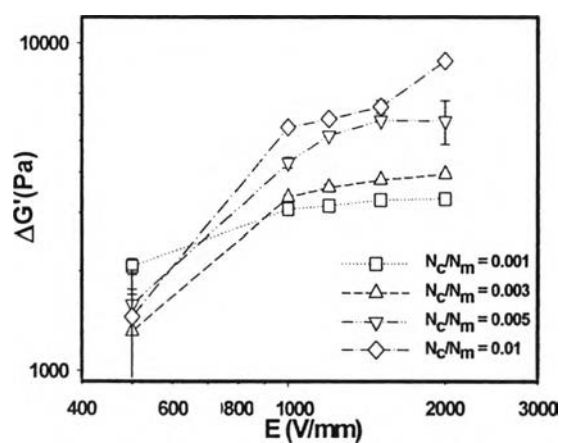
$l_0$  is the initial length of PDMS film

$F_d$  is calculated from small angle deflection approximation

$F'_d$  is calculated from large deflection approximation (using  $(l_0-l)/l_0$ )

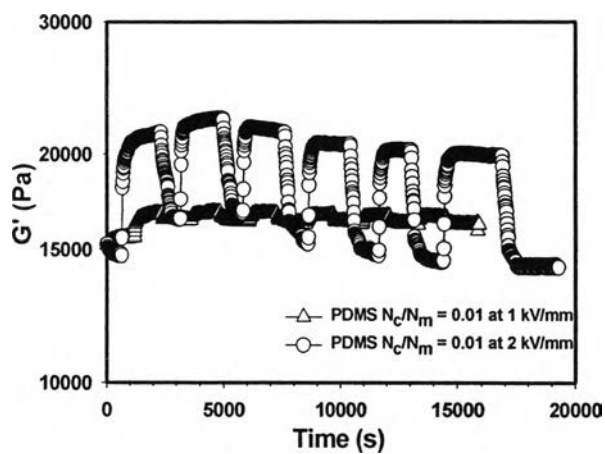


(a)

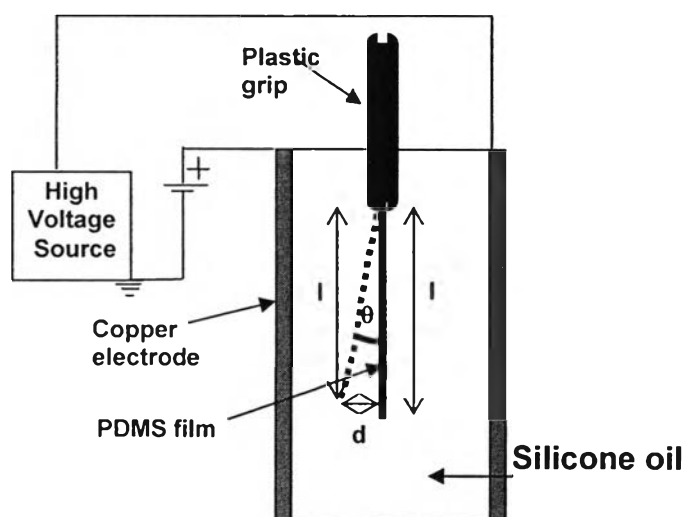


(b)

**Figure 4.1** Effect of crosslink density of PDMS: (a) storage modulus  $G'$  ( $\omega=1$  rad/s) vs. number density of strand at electric field strengths of 0, 100, 1000 and 2000 V/mm; (b) storage modulus response  $\Delta G'$  ( $\omega=1$  rad/s) vs. electric field strength, strain = 1%, and temperature of 27 °C.

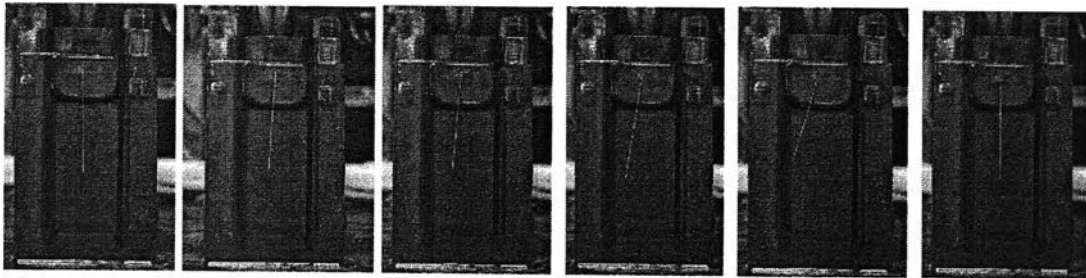


**Figure 4.2** Temporal response of PPV/PDMS90 with electric field strength of 1000 and 2000 V/mm and PDMS  $N_c/N_m = 0.01$  with electric field strength of 2000 V/mm at 27 °C, frequency of 1 rad/s, and strain of 1%.



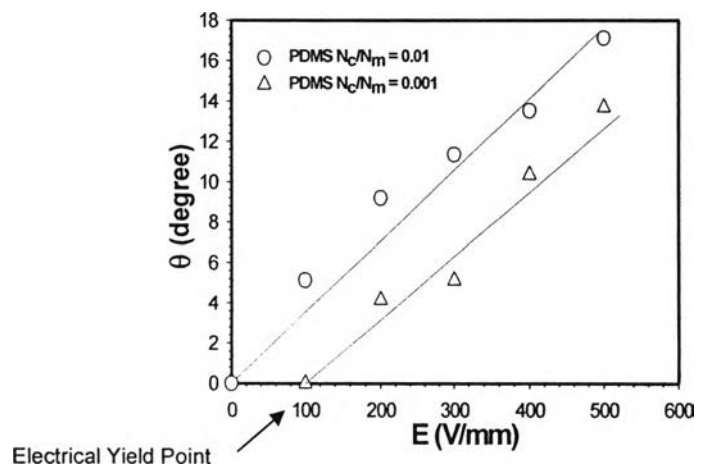
**Figure 4.3** The schematic diagram of the deflection experiment set up.



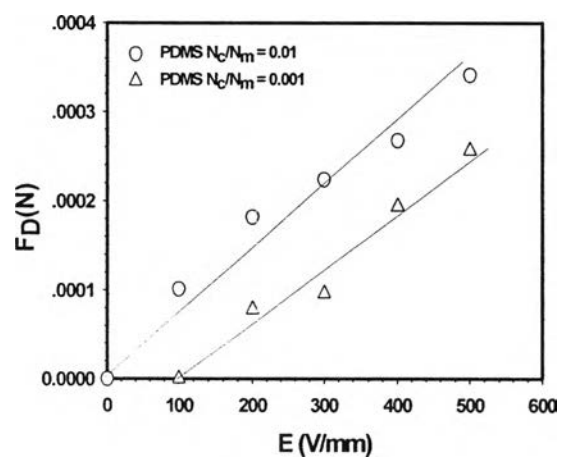


**E = 0 V/mm   E = 200 V/mm   E = 300 V/mm   E = 400 V/mm   E = 500 V/mm   after  
remove  
500 V/mm  
for 60 s.**

**Figure 4.4** Deflection of PDMS ( $N_c/N_m = 0.01$ ) film as a function of electric field strength.



a)



b)

**Figure 4.5** a) Degree of bending,  $\theta$  (degree) and b) dielectrophoresis force,  $F_D$  (N) vs. electric field strengths of the crosslinked PDMS films.