ELECTRON TRANSPORT IN FAST DIELECTRIC LIQUIDS AT HIGH APPLIED ELECTRIC FIELDS¹

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ABSTRACT

The drift velocity, w , of excess electrons as a function of the applied uniform electric field, E , in liquid 2,2-dimethylpropane (TMC), tetramethylsilane (TMS), tetramethylgermanium (TMG), tetramethyltin (TMT), 2,2,4,4-tetramethylpentane (TMP) and in mixtures of TMS with TMP (mole ratio $M = 1.31/1$) and n-pentane ($M = 102/1$, $17/1$, and $5.6/1$) has been measured for E -values up to $\sim 10^5$ V cm⁻¹. The thermal electron mobility in the above liquids is 71.5, 119.3, 114.7, 85.7, 31.8, 39.1, 118, 85, and 47.6 cm² s⁻¹ V⁻¹ respectively.

INTRODUCTION

Fast room temperature liquids (say, those with electron drift velocity $w > 1 \times 10^6$ cm s⁻¹ at an applied electric field $E \approx 5 \times 10^4$ V cm⁻¹ and boiling point $> 0^\circ\text{C}$) are finding wide applications, and are being considered for use in radiation detectors and pulsed power switches [1,2]. Such liquids are composed of "spherically" shaped molecules and they include 2,2-dimethylpropane (TMC), tetramethylsilane (TMS), tetramethylgermanium (TMG), tetramethyltin (TMT), 2,2,4,4-tetramethylpentane (TMP), and their mixtures. The fundamental electrical properties of these liquids that make them desirable in many applications and determine their usefulness are their dielectric strength (which is generally in excess of 10^5 V cm⁻¹) and their ability to transport excess electrons at speeds approaching 10^7 cm s⁻¹ [1,2]. Given the scarcity of $w(E)$ data up to high E and the uncertainty in the values of the thermal electron mobility, μ_{th} , of these liquids (see Refs. [3-5] and

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References quoted therein), we undertook a systematic study of $w(E)$ and $\mu(E)$ in these liquids and some of their mixtures. The present measurements were made with a laser photoinjection technique [3,6] unlike earlier measurements of w and/or μ_{th} in these liquids where bulk ionization techniques were used [4,5].

EXPERIMENTAL

The experimental apparatus has been described in detail elsewhere[3,6]. A somewhat similar photoionization technique was used in the past to measure w in cryogenic liquids[7]. Briefly, a laser pulse (308 nm, ~ 15 ns) struck a metal cathode and injected electrons into the liquid that drifted across the distance, d , from the cathode to the anode under the influence of an applied uniform electric field $E = V/d$. The signal was measured as a voltage (Fig. 1a) or current (Fig. 1b) waveform. From these, the drift time, τ , and then $w = d/\tau$ and $\mu = w/E = d^2/\tau V$ were determined. Numerical differentiation of the current waveforms gives the charge injection at the cathode and collection at the anode (Fig. 1c).

Analysis of the charge injection waveforms (curves in Fig. 1d) as a function of E and correlation of the injection and collection pulses can give information on the electron diffusion coefficients. The use of ultrashort pulses can facilitate this analysis; we are currently planning experiments with a ~ 500 ps laser. The liquids were purified [3] chemically (treatment with H_2SO_4 and $BaCO_3$), repeated freeze-pump-thaw cycles, passage through traps of NaOH, silica gel and activated charcoal and stirring with NaK. They were then transferred into the cell through a 0.5μ filter.

RESULTS AND DISCUSSION

The $w(E)$ and $\mu(E)$ data in neat TMC, TMS, TMG, TMT, and TMP are shown in Figs. 2a,b while the data for the mixtures are shown in Figs. 2c,d respectively. The salient features of the $w(E)$ curves for both neat liquids and mixtures are: at low fields and up to a critical field E_c , w increases linearly with E and $\mu = w/E = \mu_{th}$. For $E < E_c$ the electrons are in thermal equilibrium with the molecules of the medium and their mean energy is ~ 1.5 kT. As the field increases beyond E_c the electrons progressively gain energy from the field, their mean kinetic energy becomes greater than 1.5 kT and the

Fig. 1: Voltage (a), current (b), and charge injection rate (c) waveforms in TMG. The drift time is $\tau = 50.6$ ns and $w = 7.2 \times 10^6$ cm s⁻¹; (d) charge injection rate waveforms in TMG at various E -values.

w vs E dependence becomes sublinear. At sufficiently high E -values $w(E)$ tends toward saturation [8]. For the liquids we studied, however, no saturation was observed up to the highest field reached, $E_{\max}$ (for TMS, TMT, TMP, TMS/TMP, and TMS/n-pentane (5.6/1) $E_{\max}$ was determined by the onset of electrical breakdown). Table 1 lists the mole ratio, E_c , μ_{th} , $E_{\max}$ and the corresponding maximum electron drift velocity measured $w_{\max}$, of the liquids/mixtures studied. As a result of the larger E_c values in TMT and TMG the $w(E)$ curves in these liquids while below the $w(E)$ curve of TMS at low E cross over above it for $E > 60$ kV cm⁻¹ and 25 kV cm⁻¹ respectively. The $w(E)$ and $\mu(E)$ data of the mixtures indicate that: i) small (~ 1 to 2%) amounts of nonelectro-negative impurities do not seriously affect w (compare the $w(E)$ curves for pure TMS and the TMS/n-pentane 102/1 mixture) and ii) these impurities may actually help improve the dielectric strength.

Fig. 2: Electron drift velocities and mobilities in neat liquids (a,b) and in mixtures (c,d) (see text).

Electrical breakdown in TMS, TMP, and the mixtures occurred at $E > 10^5 \text{ V cm}^{-1}$ (see Table 1). In TMT it occurred at rather low fields ($E \approx 7.5 \times 10^4 \text{ V cm}^{-1}$) and it led to significant decomposition of the liquid and deposition of tin on the cell walls and the electrodes. In TMC and TMG no breakdown occurred up to the highest field reached (see Table 1).

Table 1. Mole Ratio M, Critical Electric Field E_c , Thermal Electron Mobility μ_{th} , Maximum Electric Field E_{max} , and Maximum Electron Drift Velocity w_{max} for the Fast Neat Liquids and Mixtures Studied.

Liquid/Mixture	M	E_c (kV cm ⁻¹)	μ_{th} (cm ² s ⁻¹ V ⁻¹)	E_{max} (kV cm ⁻¹)	w_{max} (10 ⁶ cm s ⁻¹)
TMC	Neat	3.5	71.5	116 ^a	3.3
TMS	Neat	7	119.3	125	7.2
TMG	Neat	15	114.7	109 ^a	7.4
TMT	Neat	30	95.7	75	6.0
TMP	Neat	15	31.8	115	2.6
TMS/TMP	1.31/1	18	39.1	105	3.2
TMS/n-pentane	102/1	7	118	105 ^a	6.8
TMS/n-pentane	17/1	8	95	145 ^a	6.8
TMS/n-pentane	5.6/1	15	47.6	145	4.9

^a E_{max} was not limited by electrical breakdown.

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