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ELECTRICAL INSTABILITY IN RUBY UNDER OPTICAL PUMPING

S.A. Basun, A.A. Kaplyanskii and S.P. Feofilov

Abstract - The new phenomenon consists in a spontaneous appearance in strongly excited concentrated ruby of domains with strong ($\sim$ MV/cm) electric fields of opposite sign which persist for a long time after the termination of pumping. The photoinduced formation of domains was found to depend critically on external conditions (temperature, external electric field, pumping rate and wavelength of optical excitation), as well as on the chromium concentration. Photocurrent measurements support the phenomenological interpretation of the phenomenon as a result of an electrical instability caused by the negative, absolute and differential, conductivity of concentrated ruby under optical excitation.

The electric fields in ruby, $\text{Al}_2\text{O}_3:\text{Cr}^{3+}$, were studied using the linear-in-field pseudo-Stark splitting of the R luminescence lines of ruby /1/. It was found /2/ that the symmetric doublet pseudo-Stark splitting of the lines can be observed also without application of external field, by pumping concentrated ruby samples with an Ar laser at helium temperatures. In the course of excitation the lines undergo spontaneous doublet splitting whose magnitude tends to saturate at a level $\Delta \gamma_s$ corresponding to fields $E_s$ on the order of $10^6$ V/cm. The electric field produced in the crystal persists after the termination of irradiation both at low temperatures and with the sample warmed up to room temperature.

Our experiments were performed on ruby single crystals with c-
0.3 wt% Cr$_2$O$_3$, mainly at T=77 K, using a cw Ar laser (ordinary at \( \lambda = 514.5 \) nm). The samples were thin plates with transparent electrodes deposited on both faces which were perpendicular to the trigonal axis C.

In experiments /3,4/, the sample was preliminarily irradiated to produce a photoinduced field \( E_s \) (resulting in a splitting of the R line into a doublet with \( \Delta \nu_s \)), after which an external field \( E_0 \) was applied (\( E_0 || C \)). The resulting quartet structure of the \( R_1 \) line (Fig. 1) indicates unambiguously that the photoinduced field \( E_s \) is actually spatially nonuniform, namely, that the sample contains domains in which the field parallel to C is equal in magnitude while being opposite in sign (+\( E_s \)). When an external field \( E_0 \) is applied, the total field in the domains will become different (\( E_0 \pm E_s \)). It is this effect that accounts for the quartet in the spectrum (for \( E_0 = E_s \), the field in the domains with the sign opposite to that of \( E_0 \) will become cancelled making the spectrum a triplet). The conclusion on the existence of domains with electric field \( \pm E_s \) was confirmed by experiments /4/ on the selective excitation of luminescence in domains of the same sign.

The magnitude of the photoinduced field \( E_s \) was observed /4,5/ to depend critically on temperature at which the pumping is carried out (\( P=100 \) W/cm$^2$)(see Fig. 2). At \( T<T_c = 150 \) K, the steady-state value \( E_s \) behaves in a peculiar way with \( T \), decreasing as \( T \rightarrow T_c \), while for \( T>T_c \), \( E_s = 0 \). The time in which at \( T<T_c \), the steady-state value \( E_s \) is achieved depends critically on \( T \), increasing as \( T \rightarrow T_c \). Hence for \( T<T_c \), the nonuniform state of optically excited ruby with field do-
mains $\pm E_s(T)$ is stable, while for $T \geq T_c$, the uniform state without field is stable ($E_s = 0$).

A similar critical behavior was observed /4,5/ under strong optical pumping of ruby in an external electric field $E_0$ (Fig. 3), where the critical external field $E_0 = E_s$. For $E_0 < E_s$, the spectrum (the R lines) tends to the doublet with $E_0$-independent splitting $\Delta \nu_s$ which indicates nonuniform steady state. As $E_0$ increases, redistribution of domains occurs favoring the domains with the field parallel to $E_0$. When irradiated in the field $E_0 = E_s$, the volume of the domains with the field opposite in direction to $E_0$ becomes zero, while for $E_0 > E_s$ the ordinary uniform state of the sample with the field equal to $E_0$ will now be stable.

![Graph of $E_s$ vs. external field](image)

Fig. 3 - Dependence on external field $E_0$ of measured steady-state electric field $E$ in the sample ($P=100W/cm^2$).

The dependence of $E_s$ on the optical pumping rate $P$ was studied in /2,4/. The steady state value $E_s$ decreases with increasing $P$ over the range 0.1 - 3 kW/cm$^2$ /4/ (Fig. 4) and becomes zero at $P=10$ kW/cm$^2$ ($\lambda = 514.5$ nm) /2/. When pumping in an external field, the relation $E_s(P)$ acquires a clearly pronounced critical shape /4/ implying that the nonuniform (domain) state can exist only for $P \leq P_c$ ($P_c$ depends on $E_0$).

Thus the nonuniform state of ruby with strong electric field domains is produced under intense optical pumping of concentrated ruby and is in these conditions steady-state (stable) within a limited range of external parameters: $T < T_c$, $E_0 < E_s$, $P < P_c$, $\lambda > \lambda_c$, $c > c_c$ (according to our measurements $\lambda_c \approx 400$ nm, $c_c = 0.15$ wt% Cr$_2$O$_3$ at $P \leq 100$ W/cm$^2$, $T=77K$). The transitions of optically excited ruby from the nonuniform into "ordinary" uniform state induced by variations
of these parameters are of a critical nature and occur under strictly definite values of \( T_c, E_0, P_c \). It should be emphasized that these "phase transitions" occur only under sufficiently strong optical excitation of ruby. Under weak optical excitation or in the dark, the memory of the steady-state (uniform or nonuniform) reached in strong pumping conditions may persist indefinitely long.

The photoinduced appearance of strong field domains implies a spontaneous spatial separation of charge in the sample under the action of light with the formation of space charge regions producing the observed fields \( \pm E_s \). The persistence of long-time memory after the termination of pumping shows the space charge to be localized at deep traps \((\text{Cr}^{2+})\) which at \( T \leq 300 \, \text{K} \) can be ionized only optically, and not thermally.

![Diagram](image)

**Fig. 5** - Current through sample \((P=100 \, \text{W/cm}^2)\) vs. external field \( E_0 \). Inset: theoretical \( j(E) \) dependence.

The phenomenological interpretation of the phenomenon \(^6,7/\) is based on assuming the absolute and differential photoconductivity \(^1\) of concentrated ruby in weak fields to be negative, resulting in \( N \)-shaped dependence of photocurrent on field, \( j(E) \) (Fig. 5a). With such a behavior of \( j(E) \), the state of optically excited ruby with \( E=0 \) is unstable and, conversely, the stable states are states with fields \( \pm E_s \) in which the absolute conductivity \( (j/E) \) is zero, while the differential one \( (\partial j/\partial E) \) is positive. Note that in a short circuit sample domains with opposite fields, \( \pm E_s \), should form. The observed critical behavior of the effect finds a natural explanation in the dependence of the run of \( j(E) \) in optically excited ruby on temperature \( T \), pumping rate \( P \), excitation wavelength \( \lambda \), chromium concentration \( c \) and in a sharp boundary condition for the electric instability of a state with \( E=0 \): \( \partial j(E, P, c, \lambda \ldots)/\partial E = 0 \) in weak fields.

\(^1\) The dark conductivity of ruby is extremely low.
As seen from Fig. 5a, the j(E) curve has sections \(0 < E < E_s\) where photocurrent flows against the field. This unusual situation was observed experimentally when obtaining I-V characteristics of optically excited ruby \(4,5/\) (Fig. 5). One has revealed also hysteresis in the formation of the photoelectric domain structure \(4,5/\). These results attest to the validity of the phenomenological interpretation \(6,7/\).

At the same time the microprocesses responsible for the photoelectric properties of ruby and generating the photocurrent which flows against the electric field remain unclear. In principle, such a current may be due to the presence in the centrosymmetric lattice of ruby of noncentrosymmetric polar sites differing in inversion and to the photovoltaic current associated with these sites \(5,6,7/\).

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