High resolution IR laser spectral analysis in nondestructive onco-hematological diagnostics and semiconductor technique applications

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1. Introduction

In this paper the constructed high resolution ($\leqslant 10-3$ cm^{-1}) laser spectrometer, based on IV-VI cryogenic injection lasers, is described. It can be applied in early onco-hematological medical diagnostics or nondestructive control of oxygen concentration and its distribution across Si-wafers. In such kind of spectrometer the dispersive elements are absent. Scanning of the radiation wavelength is achieved by changing the injection current. The width of the scanned spectral band is determined by the value of the laser injection current and by the duration of the injection current pulse. Using such kind of spectrometers it is possible to make not only the measurements of infrared spectra with high resolution, but also with high speed. Single spectrum in the range of $\Delta\lambda \approx 0.55$ mm can be measured within 15 ms. High resolution ($10^{-3} \div 10^{-4}$ cm^{-1}) makes it possible to resolve the superfine structure of absorption bands.

2. Experimental setup

At the earlier stage of investigations the room-temperature transmission spectra of Si-wafers and samples of dried urine at $400 \div 2000$ cm^{-1} region were obtained by means of automated system, based on grating spectrometer IKS-31 with resolution better than 0.2 cm^{-1}. For the detection of a fine structure of the bands specificic for pathological changes in urine of leukemia persons, the IR absorption spectra were investigated, using high resolution laser spectrometer ($\leqslant 10^{-3}$ cm^{-1}), based on IV-VI injection laser. The laser spectrometer was also used to obtain the oxygen concentration profiles in Si-wafers (at $T = 300$ K), because with grating spectrometer it was not possible to obtain the resolution across the Si-wafers better than 1 μm. Low sensitivity of grating spectrometer to oxygen concentration changes (worse than 10^{17} cm^{-3} in Si-wafers of 400 μm thickness) prevail the obtaining of the oxygen concentration values $N \leqslant 10^{17}$ cm^{-3} at $T \approx 300$ K.

IR laser radiation has a series of unique characteristics, the most prominent of which are high spectral brightness and narrow spectral lines. These features make it possible to carry out the measurements in conditions of low optical noise. Low temperature semiconductor injection lasers, based on lead-tin telluride solid solutions, have been used for analysis of absorption spectra within the region of $\nu = 2500 \div 700$ cm^{-1}. Scanning the radiation wavelength was done by means of the change of injection current value. The low-temperature high brightness photodetectors, based on HgCdTe, were applied. The signal from photoresistor was directed to electronic wavelength selectivity scheme and than to the personal computer, which controls the operation of the laser spectrometer. Fig. 1 shows the principal scheme of the laser spectrometer. Single spectrum in the range of $\nu = 1100$ cm^{-1} can be measured during 15 ms. High resolution ($10^{-3} \div 10^{-4}$ cm^{-1}) makes it possible to distinguish a fine structure of absorption bands (see Fig. 2).

2. Sample preparation

For Si-wafer no special sample preparations were applied. Standard, mechanically polished Si-wafers of the diameter of 100 mm and the thickness of d = 400 μm were used.

For onco-hematological diagnostics the day and night urine was collected, than it was evaporated until the sticky state at 100°C, and than dried in thermostatic chamber at 150°C for

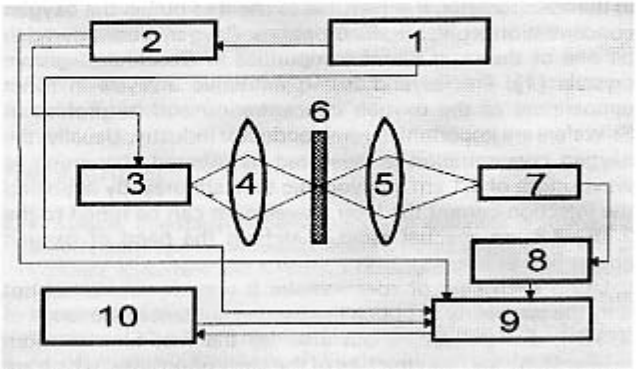

Fig. 1. Principal scheme of laser spectrometer. Denotations: *1* is the defining generator, *2* is the injection current amplifier, *3* is semiconductor injection laser, *4* and *5* are the optic lenses made of KRS-5, *6* is the sample, *7* is the photodetector, *8* is the broad band amplifier, *9* is the analog-to-digital transducer, *10* is the personal computer (IBM compatible)

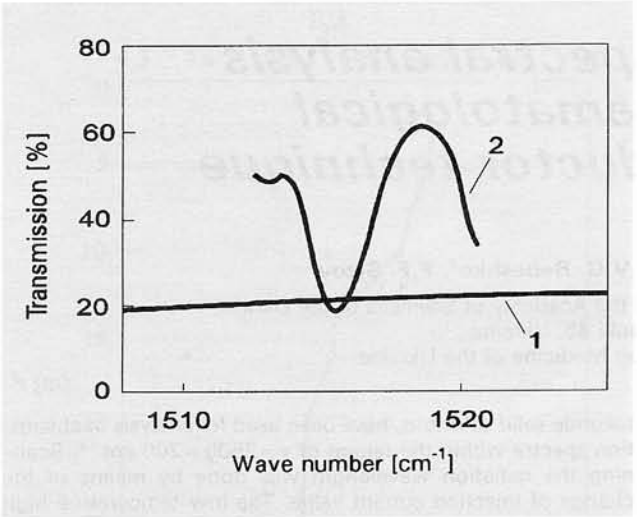

Fig. 2. The example of application of high resolution injection laser spectrometer for revealing an absorption band of Amid II in dried urine of healthy person. *1* is the spectrum obtained with grating spectrometer and *2* is the spectrum obtained with laser spectrometer

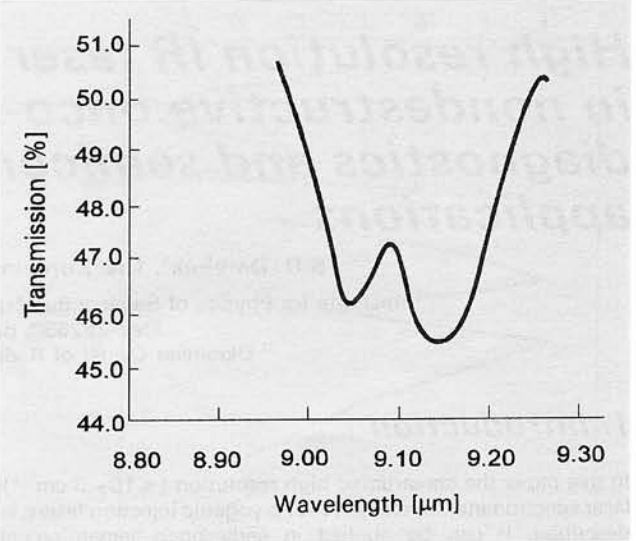

Fig. 3. Transmission spectrum of Si-wafer ($d=400$ μm, $N\approx10^{18}$ cm^{-3}) which demonstrates of the oxygen absorption in different complexes

a few hours. One gram of dried remainder was grated and pulverized in ebonite dish for 10 minutes; 0.2 g of powder was mixed thoroughly with 50 ml of vaseline oil and placed in KBr cuvette. Equal amount of samples is needed for the quantitative characteristics of relative high optical density $\alpha_d\approx0.5$ to reveal the relatively content of investigated substance in the sample by IR absorption spectra.

3. Oxygen distribution in Si-wafers

Because the semiconductor lasers of high brightness was used in the spectrometer, it is possible to use it to obtain the oxygen concentration profiles in silicon wafers. Oxygen is considered to be one of the main harmful impurities in Czochralski-grown crystals [1]. Precise and fast quantitative analysis in room temperature of the oxygen concentration and its profiles in Si-wafers are important in semiconductor industry. Usually, the oxygen concentration is measured by infrared absorption at wavelength of 9.1 μm in cryogenic temperatures. By adjusting the injection current the laser wavelength can be tuned to the $9.35\div8.8$ μm spectral band, matching the band of oxygen absorption in silicon.

Using such kind of spectrometer it was demonstrated not only the possibility to obtain the oxygen content in the range of $2\cdot10^{16}\div5\cdot10^{18}$ cm^{-3}, but also for the first time at room temperature, the fine structure of the absorption lines, which are characteristical for different oxygen positions in Si lattice, was observed (see Fig. 3).

In Fig. 4 the oxygen concentration distribution across one coordinate of the Si-wafer is shown. For demonstration of oxygen distribution profile the Si-wafer with strongly inhomogeneous O-distribution is presented.

At 77 K and threshold current of $I\approx2$ A the injection PbSnTe laser has the wavelength $\lambda=9.4$ μm. Due to very narrow half width of emission line ($\Delta\nu\approx50\div100$ kHz) the spectral brightness of such lasers is very high and is 8 to 9 orders of magnitude higher than the spectral brightness of the ordinary thermal emitting sources, in spite of rather low injection power of semiconductor laser (below 1 mW). Thus, using such kind of injection lasers, the signal to noise ratio can be increased by several orders of magnitude.

In such kind of spectrometer the dispersive elements are absent. The wavelength scanning is done by changing the injection current, which leads to the changing of the temperature of the emitting region and thus, of the band-gap of PbSnTe structure. It leads to the change of resonator length that is the reason of the modification of generation mode. Three modes can be generated in the described laser. The problem of

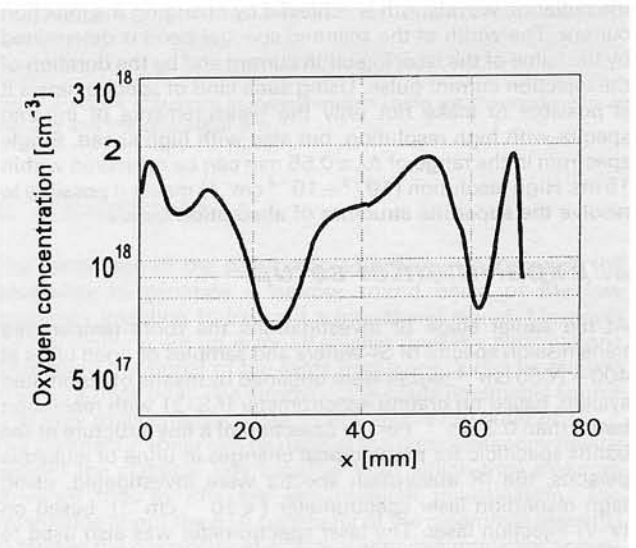

Fig. 4. Oxygen concentration profile along *x*-axis in Si-wafer

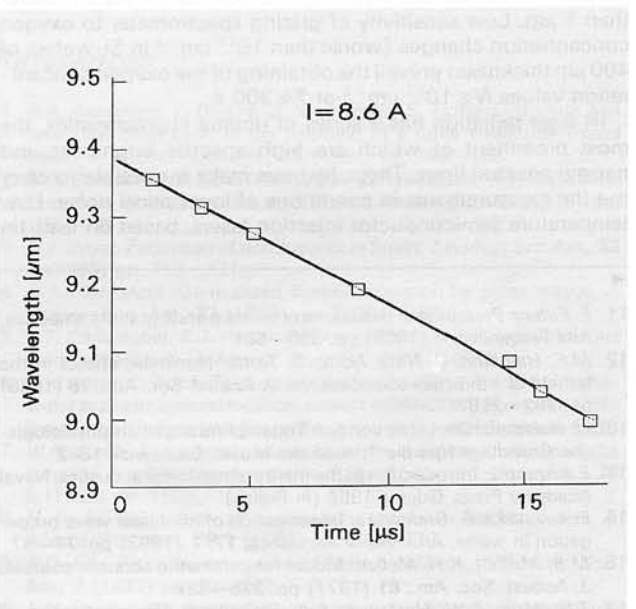

Fig. 5. Wavelength dependence of PbSnTe injection laser on current impulse duration at the current amplitude of 8.6 A

the technical realization of laser wavelength injective change may be transformed to the optimization of the injection currents and current pulses duration. For most PbSnTe lasers the dependence of wavelength on the time interval from the beginning of the laser current pulse can be obtained almost linear (see Fig. 5). The limitation of such kind of the wavelength changing is rather narrow spectral width (in this case at $T=77$ K $\Delta\lambda \approx 0.4$ μm). But for a most of high resolution or high sensitive analysis applications it is quite enough. To pass to other spectral region one needs to use the injection lasers with other chemical composition of the PbSnTe solid solution.

4. Medical applications

The laser spectrometer constructed was also applied to acute leukemia diagnostics. Acute leukemia diagnosis could be established only morphologically by discovering of distinct blast cells in blood and bone marrow. Specific external features of the initial stage of acute leukemia are absent [2]. No hematological signs could be found as well.

A most comprehensive picture could be established during bone marrow examination. In the case of acuteleukemia patients bone marrow practically always contains tenths of blast cells as comparing with cytopeny inperipheric blood. Leukemia is accompanied by infringement of osteogenesis and it is characterized by the ortho-phosphates acid forms $(HPO_4)^{2-}$ accumulation in bone apatites, hydroxyapatite contains predominantly basic PO_4^{3-} non-soluble orthophospate. Condensed forms of phosphates (pyrophosphates) could be discovered in bone and especially in urine. Thus, investigation of quantitative content of phosphate compounds in urine, which are characteristical for leukemia, by high sensitive IR-spectroscopy method, can give the possibility for onco-hematological diagnostics of the early stage of leukemia and to trace the dynamics of these elements contents during the leukemia progression.

There were carried out also some investigations of IR dried urine absorption spectra when the bone pathology took place [3]. In the case of healthy individuals, urine maximum of phosphate optical absorption is lower than protein absorption bands. If the pathology takes place, protein absorption bands become weaker while phosphate ones increase. There were investigated above 40 IR-spectra of healthy persons and above 50 IR-spectra of patients with acute leukemia. The data obtained lead us to some conclusions. In the case of healthy individuals, IR dried urine spectra consist of intensive absorption bands, characteristic for orthophosphate. In spectra of healthy persons the band are revealed, which correspond to $(CaHPO_4)$ and $CaHPO_4 \cdot 2H_2O$. The band in the range of 720 cm^{-1} is solitary and narrow. Pyrophosphate characteristic absorption bands characteristical for dried urine of patients with acute leukemia are absent.

Qualitative difference of the IR dried urine spectrum for the leukemia patients were resolved. Protein absorption bands intensity increased at 1240 cm^{-1} (Amid III). The absorption band at 1540 cm^{-1} (Amid II) can be resolved by laser spectrometer only. However, the laser spectrometer application does not allow to mark out the separate narrow bands in the range of $1030 \div 1150$ cm^{-1}, as there is superposition of the orthophosphate lines (in the case of healthy persons) or ortho- and pyrophosphate lines (in the case of patients with acute leukemia).

As the wide bands are not resolved, thus it seems to have a sense to compare the spectra configuration of the healthy and persons with leukemia at the wavelength band of $900 \div 1150$ cm^{-1}. For persons with leukemia the intense absorption (which is comparable with absorption at 1100 cm^{-1}) at wavelength bands of $920 \div 940$ and $960 \div 980$ cm^{-1} are observed. At the same time broadening of the band at 720 cm^{-1} takes place and additional absorption band at 740 cm^{-1} reveals which is connected with the presence in urine the phosphate condensed. The bands of absorption revealed can be connected with $CaH_2P_2O_7$ and $Ca_3H_2(P_2O_7)_2 \cdot 2H_2O$ compounds.

Division of the spectrum of sick person by the spectrum of healthy person let to distinguish the bands which are characteristical for leukemia process. As a result the narrow absorption band at $735 \div 740$ cm^{-1} and the intensive absorption bands at 920 and 980 cm^{-1} are revealed.

5. Conclusions

The application of high sensitive IR injection laser spectral analysis gave the possibility not only to obtain the oxygen concentration profiles across the Si-wafers and decrease the lower level of detected oxygen concentrations to $N=2 \cdot 10^{16}$ cm^{-1} (the wafer thickness $d=400$ μm) but also to reveal at $T=300$ K the thin structure of oxygen absorption in Si-wafers, presumably connected with different oxygen complexes in Si lattice. Application of this method allow to obtain the distribution of oxygen across the 100 mm diameters Si-wafers for the time of 10 minutes (with the probe step of 1 mm).

The optical absorption spectra investigations of dried urine showed that clinical consequences of acute leukemia are accompanied by structure changes of orthophosphates (from small changes in the crystal lattice of apatite up to its complete destruction) with their transformation to the condensed phosphates that is characterized by the presence of P-O-P bonds. It seems that these changes of inorganic bone constituent should be considered as compensation mechanism of the sick organism, which is directed to satisfaction of accelerated requirements of intensively proliferous pool of leukemia cells as by calcium ions, and by phosphate ions too, which are the regulators of the principal cell processes which are necessary for its vital activity. For some time these disturbances are compensated by organism, but with extension of the leukemia cells number the depot of calcium and phosphate ions (which the bone is) is exhausted, that leads to changes of crystal structure of hydroxyapatite.

Thus, the interconnections between configuration changes of infrared absorption dried urine spectra and onco-hematology diseases were found. The availability of pyrophosphate characteristic absorption bands at 740, 920, and 980 cm^{-1} are conditioned by leukemia. Because of this, investigation of infrared absorption dried urine spectra makes it possible to diagnose the leukemia and to form risk groups, not making bone marrow examination.

This work was supported, in part, by Soros International Science Foundation.

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